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2020 Annual Conference of the National Association for Clean Air

Call for Papers

CALL FOR PAPERS

The Organising Committee of the 2020 NACA Conference invites submissions of papers for the annual conference. Presenters are requested to register and submit their abstracts on the electronic submission and evaluation system. Guidelines for papers and posters will be made available on the conference page of the NACA website.

Abstract submission: 4 July 2020

Notification of acceptance of abstracts: 5 July 2020

Full papers due: 15 August 2020

Notification of acceptance and comments on papers: 30 August 2020

Authors resubmit papers if required indicating how reviewers' comments were addressed: 7 September 2020

Reviewers indicate whether comments were sufficiently addressed: 14 September 2020

Submission of final papers for inclusion in the electronic conference proceedings: 21 September 2020

FORMAT OF THE 2020 NACA CONFERENCE

In consideration of the current COVID-19 pandemic, the Council of the National Association for Clean Air has decided to proceed with the Annual NACA Conference.

Council will however confirm whether it will be hosting a virtual (online) conference or a physical onsite event.

The paper review process and technical programme of the conference will remain intact should a virtual conference be hosted - including the opening plenary, paper presentations, a poster session and possibly an online workshop.

Proceedings will be published.

The date of the 2020 NACA Conference will soon be confirmed.

CONFERENCE WEBSITE & REGISTRATION OPENS 30 June 2020

NACA LAUNCHES NEW SCHOOLS OUTREACH PROGRAMME

NACA has recently launched a Schools' Outreach Programme. The aim of the project was to create a platform of easily accessible information regarding air pollution. This information has been put together with school-going pupils at both primary and secondary levels in mind. We hope that by educating the youth on these issues we can inspire them to do their small, but important part in mitigating the effects of air pollution on both the environment and other peoples health.

The information aimed at primary school learners is presented in a colourful and entertaining manner, with a greater focus on the science in air pollution for secondary school learners.

For more information on the Schools outreach programme and the 2020 NACA Conference please visit the website at www.naca.org.za

Editorial
Clean Air Journal: supporting discussion on key African air quality issues

Editors in Chief

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The face of the Clean Air Journal changed in October 2019 with the launch of a new website and submission systems that has moved us online. Previously, each article had long email trails associated with its journey from submission to publication; this new online system has greatly assisted the Editorial Team with streamlining this process. We know there have been some teething problems with the new website, and we thank all Clean Air Journal authors, reviewers, and readers for their patience as we make this exciting change. This website has been developed as part of the Academy of Science of South Africa's (ASSAf) Khulisa Journals platform (https://journals.assaf.org.za/index). The Clean Air Journal joins seven other top South African journals in the Khulisa Journals platform that aims to support open-access South African journals.

In this issue, in addition to the regular front section that provides viewpoints and highlights on the latest happenings in African air quality, there is a featured section on air quality challenges in low-income settlements. The compilation of the contributions from researchers working in Africa on this issue aims to support the discussion in the community to share challenges, successes, and lessons learned on addressing this complex issue.

Additionally, the front material includes a call for papers for the first ever special issue of Clean Air Journal. This special issue of the Clean Air Journal will be a synthesis of atmospheric research conducted on the Highveld since 2004, and will provide an update of Tyson, Kruger and Louw (1988). It is intended to be a resource for policy-makers, managers, students, and scientists.

The Clean Air Journal is committed to supporting the African air quality research community through highlighting and supporting discussion on key topics, publishing high-quality research articles, and by providing all our material open-access.

References

Tyson, P.D., Kruger, F.J. and Louw, C.W. (eds), 1988: Atmospheric Pollution and its Implications in the Eastern Transvaal Highveld, South African National Scientific Programmes Report No. 150, Council for Scientific and Industrial Research, Pretoria

Clean Air Journal: Advertising Rates 2020

ABOUT THE JOURNAL

The Clean Air Journal publishes articles of importance to Africa in different disciplines in air quality, air pollution, its impacts on the environment and the management thereof.

The Journal is included in the Scopus and SciELO-SA journal lists for 2020, and articles published are eligible for DHET funding. The Journal is furthermore indexed in Google Scholar, SHERPA/RoMEO, and Ulrich's ProQuest.

Publication frequency

The Journal is published twice per year in May/June and November/ December (one volume containing two issues per volume). Peer-reviewed articles are published as Online Early Articles as soon as they are accepted.

Distribution and readership

The journal was visited over 5 000 times between October 2019 and April 2020, since migrating to the new Open Journal System.

The Clean Air Journal is the official publication of the National Association for Clean Air | www.naca.org.za

2020 ADVERTISING RATES

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BOOKING AND MATERIAL:

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BOOKING AND MATERIAL

DEADLINE FOR NOVEMBER/DECEMBER ISSUE
FRIDAY, 20 NOVEMBER 2020

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Clean Air Journal publishes advertisements and announcements relevant to air quality and its impact in Africa. These include advertisements of companies and organizations working in this field, announcements of conferences and workshops, and relevant job listings. NACA, the publisher of Clean Air Journal, approves advertisements published and this process is separate from the editorial process of the journal.

Announcement
Call for Papers: Special Issue of the Clean Air Journal
Theme: Air Quality on the South African Highveld

Statement of aims

The South African Highveld is the most industrialised region in Africa, and is home to around one-third of South Africa's population. Power generation, industrial, mining, transport, residential and other activities emit large amounts of pollutants into the air. Persistent anticyclonic conditions and the dry winter are unfavourable for the dispersion of pollution. Since the National Environmental Management: Air Quality Act was promulgated in 2004, the region has been subjected to numerous air quality management initiatives, including the declaration of the Vaal Triangle Airshed and Highveld Priority Areas.

This special issue of the Clean Air Journal is envisioned to be a synthesis of atmospheric research conducted on the Highveld since 2004, and to provide an update of Tyson, Kruger and Louw (1988). It will be a resource for policy-makers, students, and scientists.

Topics for the special issue include, but are not limited to:

- Atmospheric emissions
- Dispersion climatology
- Trends in and status of ambient air quality
- Impact of air pollution on human health and the physical environment
- Air quality management initiatives

Submissions

Prospective authors are requested to email their abstract to Dr Gerrit Kornelius (gkornelius@gmail.com) and Dr Kristy Langerman (klangerman@uj.ac.za) prior to writing the full paper, to ensure that the intended paper is within the scope of the special issue. Contributions will also be invited from specific authors.

Authors must submit their papers via the Clean Air Journal's online platform at https://www.cleanairjournal.org.za/about/submissions. It should be noted in a cover letter that the submission is for the special issue "Air Quality on the South African Highveld." If the manuscript is not intended as an original research paper, the cover letter should also specify if it is, rather, a review paper or commentary.

The final date for submission of full papers is **31 May 2021**.

Peer review process

All submitted papers must be original and will go through the Clean Air Journal's rigorous blind peer-review process with at least two reviewers. The CAJ's editorial policy will be strictly followed by special issue reviewers. The final decision on the acceptance of papers for publication remains with the Editors-in-Chief of the Clean Air Journal.

Accepted papers will be published immediately in an Online Early edition of the special issue. The special issue will be published online in November/December 2021. If sponsors can be found, there will also be a print version of the special issue.

Guest editors

Elizabeth Masekoameng, GIZ
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Questions regarding the special issue

Please direct any questions to Kristy Langerman at klangerman@uj.ac.za.

References

Tyson, P.D., Kruger, F.J. and Louw, C.W. (eds), 1988: Atmospheric Pollution and its Implications in the Eastern Transvaal Highveld, South African National Scientific Programmes Report No. 150, Council for Scientific and Industrial Research, Pretoria

Commentary

Air Pollution in Africa in the time of COVID-19: the air we breathe indoors and outdoors

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The first COVID-19 case was announced in Nairobi, Kenya, on the 12th March 2020. The Ministry of Health in Kenya swiftly advised physical distancing, suspended public gatherings and interschool activities, and imposed travel restrictions. In addition, the Ministry advised regularly and thoroughly washing hands with soap and water or using alcohol-based hand sanitizer. The Ministry also warned against misinformation; a call echoed by the United Nations Secretary General who cautioned against “a dangerous epidemic of misinformation” (UN News, 2020), as people searched for facts and answers which could save their lives. The coronavirus outbreak has seen these measures escalated to lockdown for many African countries including South Africa, Rwanda, and Uganda, which have been in lockdown since the end of March (Dunford et al., 2020). Other countries across the globe have also implemented different lockdown measures.

As much as the media celebrated reduction in air pollution with lockdown measures in place as a small silver lining amidst the COVID-19 pandemic, it seemed like indoor air quality was the elephant in the room given the directives for people to stay at home to curb spread of infection. This is especially so as African countries have a health and environment burden due to the increasing outdoor air pollution, but it is the indoor air pollution that has a bigger burden on premature mortality and morbidities. Exposure to indoor and outdoor air pollution is estimated to be responsible for 404,000 and 258,000 premature deaths in Africa per year, respectively (GBD, 2017). Air pollution (both indoor and outdoor) accounts for over 14% of all non-communicable diseases (NCDs), a far greater share than the contribution of other key risks factors including alcohol, diet and high sodium intake (GBD, 2017). This exceeds mortality due to unsafe water, sanitation, and childhood malnutrition in Africa (Rees et al., 2019). Furthermore, there is added risk because NCDs, which are pre-existing conditions that increase the risk of death for COVID-19, are the diseases associated with the increase in exposure to air pollution. Preliminary results find that among the U.S. population, an increase of only 1 $\mu g/m^3$ in $PM_{2.5}$ in the long-term is associated with a 15% increase in the COVID-19 death rate (Wu et al., 2020). In Europe, early results show COVID-19 fatalities were greatest in the regions with the highest long-term exposure (Conticini et al., 2020). Therefore, in Africa, COVID-19 fatalities and air pollution are likely to further overstrain health systems which already suffer from a disproportionate burden of communicable diseases like malaria, cholera, Ebola, and dengue fever.

More than 900 million people in Africa rely on polluting energy sources for cooking, and 600 million are without access to electricity (IEA (International Energy Agency), 2019). This means, during the COVID-19 period, millions of households in Africa are exposed to high levels of air pollution as they cook, heat and use light inside their houses. The exposure to air pollution from the burning of wood, charcoal and kerosene in these households is exacerbated by many millions living in small congested spaces, poor ventilation and building materials that increase the pollution load. These living conditions are encountered globally in informal settlements, where close to one billion people are estimated to live (Corburn et al., 2020). Furthermore, in the poorer households, most families will use whatever is available for fuel: scrap tires, plastic waste, cloth rags and other unconventional materials (Muindi et al., 2016). A study in Nairobi in an informal settlement showed the levels of fine particulate matter communities were exposed as they went about their daily activities were approximately 3 to 4-fold the World Health Organization (WHO) Air Quality Guidelines for outdoor air quality (West et al., 2020). When the indoor and outdoor air pollution mean values were compared, indoor air pollution concentrations far surpassed the outdoor air pollution values. Thus, during the COVID-19 period where most households are required to be indoors, it is most likely indoor air pollution exposure will increase, adding to the underlying vulnerabilities of people already exposed to long term high levels of outdoor air pollution. Moreover, air pollution exposure is unevenly distributed and inherently unjust in Africa as poor communities are most likely exposed to higher levels because their houses and workplaces are close to major roadways, industrial parks and waste dumps (Rooney et al., 2012; Egondi et al., 2016). This is compounded by poor health access and nutrition. As parts of Africa transition towards colder weather and as households face economic hardship, there may be more use of dirty fuels further worsening indoor pollution.

The traffic in most cities in Africa during the COVID-19 shutdown has reduced, such that the easing of congestion is seen to be like the traffic thinning during the festive period where most city dwellers decamp to the rural area for short periods. The question of the cleaner air in African cities however is most likely more complex than the optimistic reports of clean skies and fresh air in cities: New York (Mcshane, 2020), Los Angeles (Kann, 2020), London (Edwards, 2020), Milan (Buonocore, 2020), Wuhan(World Economic Forum, 2020), Beijing, Bogota (Petersen et al., 2020) and New Delhi (Gettleman, 2020). The ease in which the evidence could be provided on the declining levels of outdoor air pollution in cities in the U.S, Europe and Asia, may not be for African cities. This may be because there is a dearth of ground air quality monitoring in African cities. Less than 10 countries in the African region have ground-based city level data on air pollution including PM_{10} and $PM_{2.5}$, representing only 0.5% of cities in the region(WHO, 2018) . But among the cities with data, 90% of them exceed the WHO guidelines for PM. There is also limited air pollution epidemiological studies conducted in Africa (Coker and Kizito, 2018). Furthermore, epidemiological studies obtained in developed countries may not be extrapolated with complete confidence to African countries (Wichmann, 2005). Thus, it is clear there an air pollution problem in Africa, but we need to build the evidence base (Wichmann, 2016).

Globally, outdoor air pollution has declined in 27 countries in the first two weeks of lockdown: nitrogen dioxide (NO_2) by 29%, Ozone (O_3) by 11%, and fine particulate matter ($PM_{2.5}$) by 9% (Venter et al., 2020). This decline has been attributed to lower emissions from transport and industry related activities. Scientists have cautioned for these studies to be interpreted against the seasonal meteorological variation (Carslaw, 2020; McNeill, 2020; Young, 2020). However, these analyses are often not possible in Africa where the limited ground air quality monitoring is often sparse, short term, piecemeal and where most of these campaigns are to test new technologies, and thus the scarce resources are not often targeted towards the local problems but rather at the external project priorities.

Amid the COVID-19 pandemic the potential for innovation in Africa has come to the fore, new ways to tackle hygiene in a water scarce environment for example comes to mind. A recent invention by Kenyan youths for example, mounts a mobile wash facility on a bodaboda (motorcycles commonly used for goods and passenger transport) that dispenses soap, water and masks, and recycles the water used; this is all assembled using recycled material (Shiundu, 2020). Leveraging these kinds of efforts to tackle air pollution challenges may be the targeted interventions African governments need. However, the rollback or the loosening of air quality limits during the pandemic (McNeill, 2020) or after in some parts of the world is action African governments can ill afford. Whilst indoors, households are advised to reduce indoor air pollution by increasing ventilation by opening windows, doors and if undertaking activities such as cooking, heating or lighting leaving these open for as long as possible. Furthermore, the relief packages considered for the vulnerable members of the communities in Africa may consider clean fuels as part of the package to alleviate exposure due to burning of dirty fuels. Additionally, as evidence on spread of COVID-19 in Africa is built there is a need for the modelling to consider environmental factors including air quality as well as trends in fuel usage.

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Commentary

On the importance of considering land surface reflectance in earth system studies

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If we consider the disciplinary divisions which make up earth science: ocean-atmosphere, land-atmosphere, hydrosphere, cryosphere, and stratosphere-troposphere, we can see the acknowledgement of the importance of the surface of the earth in understanding the stocks and fluxes of energy, water and matter. Yet understanding the features of the land surface lag behind our understanding of atmospheric chemistry and the health impacts of air pollution. This raises a philosophical question: 'if we are unable to understand the land surface accurately over a range of temporal and spatial scales, how confident can we be in our understanding of the earth system?'.

Response variables which measure structural conditions, as such the normalised difference vegetation index (NDVI, which measures greenness) and the fraction of absorbed photosynthetic active radiation (FAPAR), have been critical in allowing us to begin to assess the human impact on the earth system, and gain some insight into the magnitude and patterns of the risks to social-ecological systems. But we need be more creative. To this end, I suggest albedo as a key variable to consider using from the suite of routinely measured variables. Albedo measures the reflectivity of a surface to solar radiation, a ratio of the amount reflected to the amount of downwelling radiation, and has many attributes which make it suitable for answering questions which are systemic in nature: in particular, it can be measured at a range of scales, and technological advances mean that hand held instruments and satellite-based products cover opposite ends of these scales, making the measure accessible from local to global levels. At regional to global scales, satellite observations provide long time series for objective analysis of the human impact. Linking local to broader scale measures allows us to study how albedo impacts propagate across scales (Scholes 2015).

Surface albedo is a joint property of the sun, atmosphere and the earth's surface because it is determined by both the incoming and reflected radiation fluxes. It is a responsive indicator of land-atmosphere process interactions, but the interpretation depends on the spatial and temporal resolution of the dataset as well as the attributes of the environment in question. For instance, between seasons and years it can be used as a proxy for leaf emergence, as in the case study of the use of cover crops in Europe (Carrer et al. 2018). Over decades it could be used to assess species composition and structural/functional changes due to land use change, disturbance such as fire and wood harvesting, ecological succession or ecosystem rehabilitation (Halim et al. 2019).

The resolution of the measurement and the extent of the heterogeneity of the system being studied - for example in topography, vegetation structure and species composition – will determine what is being integrated. Measurements with a hand-held instrument with a small field of view might measure the albedo of a single leaf, while a more remote instrument will measure the albedo of the canopies of multiple plants species and soils with varying moisture levels. In moving from the leaf level to the community level and higher, we are able to assess different ecosystem characteristics and processes.

Understanding the patterns and trends of land degradation and desertification remains a key challenge facing scientists today. In the 1970's Joseph Otterman, Jule Charney and colleagues looked at changes in albedo to build a hypothesis about the desertification in the Sahel region. What was observed is typical in semi-arid and arid areas: vegetation loss results in an increased albedo and less energy is absorbed at the earth's surface. This means that relatively less energy then returns to the atmosphere as sensible and latent heat, which promotes the subsidence of air aloft and which may in turn reduce precipitation. The role and impact of land cover changes on albedo and the persistence of drought has remained controversial largely because of the influence of the climate belt/latitude where the changes occur, the role of water balance and different scale perspectives have not been reconciled.

To compare land-atmosphere interactions the Intergovernmental Panel on Climate Change popularised the use of the radiative forcing (RF) metric. This influenced later work with albedo which focused on comparing biophysical processes with biogeochemical processes. These trade-off assessments were highlighted by Richard Betts in 2000, who showed that negative forcing (or cooling) due to the carbon gains from forestation may be outweighed by the positive forcing (or warming) due to the lowering of albedo in boreal forest systems.

Since then the focus on mid-to-high latitude forest systems has continued, and the topic of albedo has largely been neglected for arid and semi-arid systems. The observation of greening in the Southern hemisphere due to La Niña in 2011 then highlighted the dominate role of these regions in the global carbon sink and its interannual variability (Poulter et al. 2014). Modellers have since agreed that regional characteristics, land cover changes and related feedbacks processes in current climate models have been neglected, and a closer look at the Coupled Model Intercomparison Project Phase 6 (CIMP6) ensemble run further underscores the importance of understanding the albedo in semi-arid systems (Jain et al. 2020).

Now international agreements and partnerships which seek to manage climate through the drawn down of atmospheric CO_2 through tree planting in grassy or savanna ecosystems, such as the Bonn Challenge and the AFR100 off-shoot, demand that we return our focus to Africa. We cannot accept a one-size-fits-all approach. The biophysical nature of our systems must be understood in all their variability so that we can maintain and conserve them. This biophysical conservation means that the benefits and drawbacks of any intervention need to be assessed at both a local and global level. The utility of albedo and surface energy budgets need to be communicated effectively across disciplines for a holistic assessment of net benefits to be achieved.

Efforts are being made to expand biodiversity stewardship agreements and extend the areas under formal conservation, while at the same time food demands increase and mining, urbanization and agricultural practices require more space. Albedo can be included as an informative variable in typical conservation concerns including the effects of habitat fragmentation, patch effects and species change and loss. It can be used to assess the impact of slimes dams of the radiative energy budget and potentially on rainfall. From these data we can contribute to better informed ecosystem management and restoration agendas.

The intentional manipulation of albedo, so-called “albedo enhancement”, falls within the geoengineering climate mitigation strategies, and include approaches such as seeding clouds to reduce incoming solar radiation, or increasing the areal cover of pale surface to reduce the heat island effect in urban environments. Albedo manipulation has clearly captured the interest of purveyors of high tech solutions, while at the same time making up a fsundamental part of many climate change narratives, including sea ice melting (the well-known ice-albedo feedback at high latitudes), and thus should be included more explicitly in biology, chemistry, physics, meteorology, hydrology and ecology related fields.

A wealth of land surface data has already been collected and can be accessed through a number of channels. To access data that have already been collected, there are multiple satellite missions with otherwise well used products which offer albedo, such as NASA’s MODerate-resolution Imaging Spectroradiometer (MODIS). Online interfaces such as APPEARS (portals) and Google Earth Engine (GEE, coding interface) are diversifying the access to the datasets and removing the limitations of data handling and storage. In South Africa, high resolution surface products from Multi-angle Imaging SpectroRadiometer (MISR) are processed at the Global Change Institute at Wits University (Verstraete et al. 2012). The multi-angular distribution from the instrument makes for a better constrained and therefore more accurate albedo at our disposal.

Despite the concept of albedo being relatively intuitively understood, its use in research is surprisingly sparse, and it is currently used within only a few specific disciplines. Land surface albedo should be key variable measured and used during future field campaigns, synthesis studies, databases, and modelling. The challenges facing us now and in the future are complex, and require trans- and inter- disciplinary work. The breadth of use of albedo can play an important part in the growth of an integrated earth system science and the shift to a holistic land management paradigm.

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Research brief

Dust and Radon Levels on the West Coast of Namibia – what did we learn?

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Windblown dust from natural mineral sources is estimated to account for up to 89% of the global aerosol load, with anthropogenic sources accounting for 8%. Within the southern African region, Namibia is the main source of mineral dust where episodic dust storms associated with strong easterly winds give rise to mineral dust emissions from both natural as well as anthropogenic sources. High concentrations of particulates in the air pose a risk to human health and welfare, with no safe threshold for exposure to PM_{10} and $PM_{2.5}$ according to the World Health Organisation (WHO, 2000).

A study conducted in the Erongo Region of Namibia in 2010, indicated PM_{10} concentrations to be elevated in the towns of Swakopmund and Walvis Bay, with windblown dust from natural and anthropogenic activities as the main contributors. Exposure to ionising radiation associated with the inhalation of windblown dust, as well as from radon progeny, were identified as potentially harmful to human health. Between 2016 and 2019, this study was updated and extended, with an ambient monitoring network established to measure particulate matter and radon concentrations at three locations (i.e. Walvis Bay, Swakopmund and close to the town of Arandis). In addition, the emissions inventory and dispersion model were updated, and the results validated against the ambient monitoring data.

Elevated PM_{10} concentrations were recorded at all stations, except at Henties Bay. $PM_{2.5}$ concentrations, only measured at Swakopmund and Walvis Bay, reflected similar temporal variation as the daily PM_{10} concentration trends, but at levels well below the WHO guideline. The highest PM_{10} concentrations were found to occur during east-wind conditions, with higher concentrations recorded at the coast than at inland locations. At Walvis Bay and Swakopmund, high PM_{10} concentrations were also recorded during westerly and south-westerly wind conditions, when marine biogenic aerosols and sea salts are emitted due to wind friction on the sea surface. The contribution from sea salt was confirmed through chemical analyses, where the average sodium content in the PM_{10} was 6.1% at Swakopmund and 4.5% at Walvis Bay.

Modelled results only accounted for anthropogenic sources, as windblown emissions from natural sources could not be modelled with any degree of certainty. Vehicle entrainment from roads (i.e. paved, unpaved and salt/treated surfaces), followed by mining and quarry operations, were found to be the main anthropogenic sources contributing to PM_{10} and $PM_{2.5}$ emissions. Modelled results from these sources were low, especially at the coastal receptors, indicating natural sources to be a significant contributor to particulate matter (PM) concentrations.

The measured and modelled results were used to recommend PM guidelines for the Erongo Region, where the South African National Ambient Air Quality Standard for PM_{10} and the WHO Interim Target 3 for $PM_{2.5}$, were recommended, but with more allowable exceedance days due to east-wind conditions and the presence of sea salt.

The radiation-related public exposure doses due to the inhalation of radon, radon progeny and radioactive dust were quantified using real-time empirical results for ambient atmospheric radon concentrations, and radionuclide concentrations from select PM_{10} samples. The contributions of both radon and ambient radioactive dust to the public exposure dose in the Erongo Region were found to be well-below the world-wide average doses suggested by UNSCEAR and other international bodies.

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Commentary
Some observations about air quality in dense, low-income settlements

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For decades, research on air pollution in low-income urban areas of South Africa has emphasised domestic solid fuel burning as an important source of pollution. In the Vaal Triangle and Mpumalanga Highveld, domestic coal use, especially for space heating in winter, was the subject of much research and a number of successful interventions.

Formalisation of housing, electrification, reduced availability of coal burning devices (due to the closing of the Falkirk plant in Newcastle and the fact that paint is not sold in metal tins anymore) in addition to above inflation increases in the price of coal, lead to a steady decrease in the proportion of households who use coal. A recent analysis of long-term trends in air quality in the Vaal Triangle Airshed Priority Area and the Highveld Priority Area (Feig et al. 2019) showed that there is indeed a steady, albeit in some cases slow, decrease in particulate concentrations in these areas.

There is certainly progress in the fight against air pollution in low-income urban areas. There are however counter forces. I will briefly discuss the following: population growth, urbanisation, electricity price increases and supply disruptions, collapse of infrastructure and failure of services.

Population growth. Comparison of the last three national censuses shows that although there is a large drop in the proportion of households who use solid fuels as their primary energy source for domestic cooking or heating, the drop in absolute numbers is not as dramatic. Between 1996 and 2011, the proportion of households who use wood as their primary energy source for cooking dropped from 22.9% to 13%. When the absolute numbers are compared, the picture is less dramatic. In 1996, a total of 2,07 million households used wood for cooking, this increased to 2,3 million in 2001 and decreased to 1,8 million in 2011 (Statistics South Africa 2004, Statistics South Africa 2012). This means that the almost 10% proportional decrease in wood-using households only corresponds to an absolute decrease of only around 265 000 fewer households. The future number of people exposed to air pollution from domestic sources will depend on the race between population growth, and economic and technological development.

Urbanisation. In 1996, 57.6% of 42.24 million people in South Africa lived in areas classified as urban (Statistics South Africa 2003). This increased to 66% of 57,78 million people in 2018. This means that over a period of just over two decades, the population of urban areas in South Africa has increased by almost 14 million people. To place this in perspective: over the same period the total growth in population was approximately 15.5 million people.

In spatial terms, one of the ways in which the phenomenon of urbanisation happens is as a cycle of settlement, densification, de-densification and re-densification. *Settlement*: This cycle starts with the informal settlement of an area of vacant land. This may take place organically at the fringes of settlements. It may also happen in an organised manner – evidenced by regular layout and sudden appearance of structures. In the beginning of such a new settlement, structures may be small and are spaced sparsely. *Densification*: After its initial establishment, settlements typically densify over time as more and larger structures are erected. Partial formalisation may also take place as services are provided and formal structures either allowed or provided. In cases where informal settlements are been upgraded in-situ, households may keep their informal structures or erect new ones next to the new formal houses (either for own use or as rental units). *De-densification*: De-densification of an already settled area corresponds to the settlement of a new area by backyard dwellers who want a place of their own. *Re-densification*: Takes place when backyard shack are let out to new tenants after the original tenants have moved away due to a settlement event.

Electricity price increases and supply disruptions. Most of the readers of this journal will not need to be convinced that electricity prices have increased dramatically since 2008 and that supply interruptions are episodically common. Using solid fuels is not as comfortable as using electricity but it remains effective and economical in situations where bulk thermal energy is required. This is the reason why more households use solid fuels for space heating than for cooking. The more expensive and unreliable electricity becomes, the stronger the incentive towards solid fuel use. We also have recently started observing

[1] It is well known that households in South Africa often use a mix of energy carrier and that therefore total solid fuel use is drastically underestimated by the census (see Pauw et al. 2013).

a growing use of liquid petroleum gas (LPG) – attributed by respondents to unreliable electricity supply.

Service delivery failure. Absence or failure of waste removal services is common in dense, low-income settlements in South Africa. Residents resort to alternative waste management practices that include using informal waste dumps. The physical and social geography of these dumping areas are interesting; they are typically situated relatively close to households (determined by how far one can comfortably walk with a wheelbarrow) on a piece of no-mans land. These sites can remain stable over years. In Sharpeville we tracked an informal dumping site that remained on the same side of the footpath for nine years. The stability of these sites and their predictable locations show that this practice should not be seen as simple littering. Given the circumstances, burning waste on private stands or at communal waste heaps is not a completely unreasonable course of action. Compared to research on domestic fuel use there is little research on the extent and possible solutions to urban waste burning.

The underlying cause of the type of air pollution specific to dense, low-income settlements in South Africa is poverty. People generally do not like to live in dust and smoke, and take measures to avoid it if they have the means to do so. A recent study has shown how air quality in two settlements (Kwazamokuhle and Hendrina) located very close to each other differ dramatically. The main underlying reason why air quality in Kwazamokuhle is so different from Hendrina is because average income in Hendrina is higher and has been higher for decades.

It is investment in infrastructure and long-term and equitable economic growth that will eventually reduce air pollution from unpaved roads, waste burning and domestic solid fuel use. Where this has taken place (e.g. provision of formal houses and electricity), the successes are already apparent.

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Commentary
Using citizen science to assess cumulative risk from air and other pollution sources in informal settlements

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Environmental challenges in informal settlements

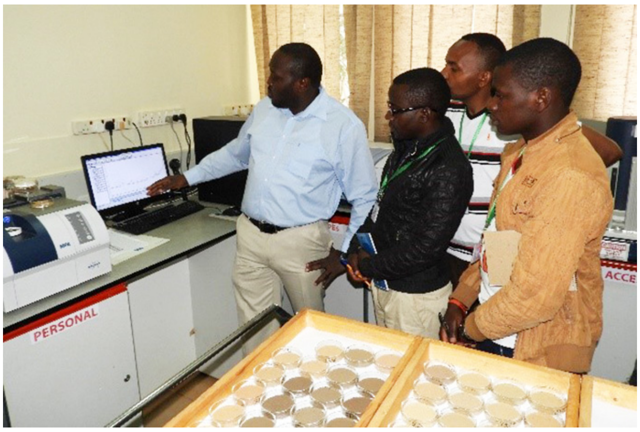
Residents of informal settlements in developing countries such as Kenya are faced with a myriad of environment challenges that exposes them to a combination of risks from multiple exposures to environment stressors, including pollution and environmental contamination. Researchers and development planners usually focus on and typically address a single environmental issue, such as air pollution, rather than to take a holistic approach that considers the combination of risks, that cumulatively affect these residents due to multiple exposure. This lack of a holistic approach is made worse in informal settlements that are considered illegal, unplanned and therefore ignored in urban development frameworks (McCartney& Krishnamurthy, 2018; Jones, 2017). The sustainable development goals (SDGs), including the New Urban Agenda (NUA), which emerged from SDG 11 presents policy opportunities for a holistic approach to urban development, given the attention paid to the progressive and democratic approaches such as liveable, inclusive, and just cities. The focus of the New Urban Agenda (NUA) of "leaving no one behind" has generated positive responses in some African countries, which, taken together with the African Union's Agenda 2063 can lead to sustainable cities in Africa (UN 2019).Given the uniqueness of cities in Africa, homegrown models present the most suitable opportunities for the realisation of sustainable cities, and to achievement of all the 17 SDGs. Transdisciplinary research models is central for African cities as it enables scientists, practitioners and local communities to work together to co-generate solutions that are embedded in local realities and context (International Council for Science 2020).

The case of Mukuru informal settlement in Kenya illustrates the challenges of cumulative risks from air and other pollution sources, and the opportunity that is presented by a trans-disciplinary approach to research that involves local communities, practitioners and policy makers to co-create solutions that are based on the local contexts. Mukuru, which comprises of three informal settlements (Mukuru Kwa Njenga, Mukuru Kwa Reuben, and Viwandani), is situated approximately 7km to the south eastern part of Nairobi CBD, and occupies an area estimated at 670 acres, with a population coverage of 100,561 households. Due to its unique circumstances, the

A group of youth from the Mukuru settlements (Community Champions) involved in soil sample collection. Photo credit: William Apondo, SEI

Nairobi City County Government (NCCG) declared Mukuru as a Special Planning Area (SPA) invoking, for the first time in Kenya's history, Article 23 of the Constitution of Kenya (2010), which give the County Governments power to designate an area as SPA, if distinguished by unique development problems and environmental potential while also raising significant urban design and environmental challenges.

The SPA approach embraces the spirit of urban inclusivity, which is supported by the Government of Kenya and other development partners that recognise the important role that informal settlements play in the urban economy and accommodation of a large section of urban residents. In Mukuru, the SPA process did not only focus on improvements to the physical infrastructure, but also provided for participatory frameworks that has allowed the urban poor to be able to engage with policy makers and present the issues affecting them, which was hitherto often downplayed. Historically, urban planners have tended to give preference to purely technocratic-driven interventions, that rarely addressed the wider environmental challenges such as the rampant pollution that is prevalent in informal settlements, leading to undetected exposure of residents to alarming levels of pollution, that is considered as the largest environmental cause of disease and premature death in the world (the Lancet Commission 2017) .



ICRAF scientists conducting training for Community Champions and CHWs from Mukuru on soil sampling, analysis process and packaging of soil samples. Photo Credit: William Apondo, SEI.

Multiple cumulative exposure from air and soil pollution

The SPA provided a unique platform for the formation of a multi-stakeholder, multi-disciplinary and cross-sectoral team of over 40 organizations led by the NCCG and the Slum/Shack Dwellers International (SDI) that worked together in eight Consortia to develop the Integrated Plan for Mukuru (Horn et al., 2020). The Stockholm Environment Institute (SEI), as convener of the Environment and Natural Resources SPA Consortium, together with the NCCG (Environment Department), SDI, and the World Agroforestry (ICRAF) conducted studies on waste management, air pollution and soil contamination, to provide scientific evidence to inform the Mukuru Informal Settlement Plan. These studies followed a transdisciplinary approach, by using citizen science methods, training and working with community champions (selected individual youth) and community health workers (CHWs) drawn from the local communities in the process of data collection. The findings from the studies on waste management, air pollution and soil contamination, validated previous studies that highlighted the environmental threats to health and well-being among residents in Mukuru arising from both indoor and outdoor air pollution (West et. al., 2020; Dianati, et al., 2019; Muindi et al., 2014), soil contamination (Ondayo et. al., 2016), water pollution, and lack of sanitation and hygiene (University of California Berkeley: UCB, 2018).

The studies on the three environmental components; waste management strategies employed, air pollution, and soil contamination, may seem to deal with different aspects, but are in essence, combined in a way that exposes the multiple and cumulative exposure to the residents of Mukuru, and should therefore be addressed collectively and in an integrated manner; soil health, waste pollution and air pollution are intrinsically linked and were noted to contribute to overall quality of the environment in Mukuru. This is a rare cumulative analytical approach that would be suited for other high or a low-income urban settlement in Kenya and Africa, and is critical in analysis of informal settlements livability suitability by depicting the level and nature of pollution exposure and associated health risks at household and community levels. UN Habitat & WHO (2020) encourages application of detailed exposures and relative risk estimates to aid in deriving net health impact of combined exposures in everyday living in environment which should inform planning and decision-making processes around urban and territorial interventions.

Informal settlements are spatially located in delicate environments (often low-lying areas near river banks that are prone to flooding and other disasters) and are often without any form of buffers. These conditions exposes the already socially and economically vulnerable residents to harsh living conditions physically and financially. This creates high chances of the residents being trapped in poverty as they are forced to use their meager resources to treat illnesses that are caused by pollution, such as respiratory health conditions that is associated with cooking using dirty fuels, open burning of waste, and emissions from the industries, as well as contamination of food that is grown in polluted soils using water from polluted rivers and streams.

The air quality studies in Mukuru have focused on three major pollutants; particulate matter ($PM_{2.5}$) Nitrogen dioxide (NO_2) and Ammonia (NH_3). PM levels were found to be variable with indoor peaks in the mornings and evenings, and outdoor locations recording concentrations of between 15 – 70 µg m^{-3} for daily averages, against the World Health Organization (WHO) guidelines of 25 µg m^{-3}. Similarly, areas close to industries recorded high levels, exceeding the Kenyan and WHO standards (West et. al., 2020; Twigg, 2018). The NO_2 levels recorded across nine sites in Mukuru were below the annual national air quality regulations tolerance limits in Kenya of 150 µg m^{-3} and at least one location was above the WHO annual mean guideline of 40 µg m^{-3} (WHO, 2005). The NH_3 levels in Mukuru were found to be very high across the nine measurement sites, with an average concentration of 45.73 µg m^{-3}, compared to a low of 3.45 µg m^{-3} recorded at a reference background site located at the World Agroforestry Centre (ICRAF) in Gigiri, close to the Karura forest (Twigg, 2018). Open dumpsites littered with solid waste and free flowing human waste due to lack of proper sewerage system were identified as potential sources of NH_3 (Apondo, 2019). Previous studies suggest that, open waste burning is also an important contributor of PM source in the city (Gatari et al 2005). This may therefore require that planning interventions address simple guidelines of handling waste and proper siting of waste collection sites to reduce exposure to air pollution in such settlements through responsive urban design and air quality monitoring.

Other aspects associated to exposure to air pollution in Mukuru included crowded housing with a density of 87,538 persons per km^2 (by comparison, this is higher than Kibera Slums with a density of 15,311 persons per km^2 and far much higher than Cape Town's Khayelitsha slums with a density of 10,120/km^2). This is worsened by the poor housing conditions, which are either completely lacking or have inadequate ventilations.

The soil contamination study focused on the following elements, arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), molybdenum (Mo) nickel (Ni) and zinc (Zn). The levels of heavy metals such as Cd ranged from 1.23-22.73 mg/kg, which was higher than the tolerable values of 3mg/kg. Zn ranged from 230.81-4979.67 mg/kg, which is extremely higher than the tolerable value of 300mg/kg. These values suggest contamination of Zn and Cd due to the waste dumping site and the industrial activities around the area. One of the most important analysis connecting solid waste and soil pollution to air pollution is that soils are the major sink for heavy metals released into the environment.

Soil contaminant limits for heavy metals in urban areas have not been developed in Kenyan. The contaminant limits for heavy metals have been developed for soil total element concentration values in attempts to determine and predict concentrations above which effects occur and below which effects do not occur (Chapman et al., 2003, Towett et al., 2013), these values however vary by jurisdiction. Airborne sources of metals in soils include all solid particles in smoke from fires including burning of waste, and in other emissions from factory chimneys which according to Smith et al (1995) are eventually deposited on land; most forms of fossil fuels contain some heavy metals, and this is, therefore, a form of contamination which is in large scale since the industrial revolution began. Previous studies in informal settlements in Nairobi including Mukuru found high concentrations of Pb, with children exposed to levels beyond the USEPA limits (Ondayo et. Al., 2016). Also, USEPA (1996) noted that very high concentration of Cd, Pb, and Zn has been found in plants and soils adjacent to smelting works. Another major source of soil contamination is the aerial emission of Pb from the combustion of petrol containing tetraethyl lead; this contributes substantially to the content of Pb in soils, especially those sampled along the roadsides in urban areas and in those adjacent to major roads. Zn and Cd may also be added to soils adjacent to roads, the sources being tyres, and lubricant oils.

Conclusion

Residents of informal settlements are faced with multiple risks including cumulative exposure to air, soil, and water pollution. These environmental issues are often addressed in isolation and rarely are there integrated and holistic approaches. Transdisciplinary studies, including citizen science approaches that brings together scientists, practitioners, policy makers and local communities in informal settlements to co-create solutions hold promise for promoting holistic and integrative approaches. In this commentary, we presented an example of how an inclusive and participatory policy approach for planning of an urban informal settlement in Nairobi has presented the opportunity for collaborative co-creation of solutions to address the multiple and cumulative challenges of pollution from air, soil and other sources in Mukuru informal settlements in Nairobi. Cumulative pollution analysis is likely to catalyse desired urban planning interventions to realise the goals of attaining inclusivity and liveability in informal settlements. This is useful in addressing the complex environmental quality challenges that the vulnerable urban community living in informal settlements experience on daily basis as demonstrated in the Mukuru case. Involvement of community champions in data collection is important in creating awareness and sensitization among the residents as they can use their knowledge and experience to help community aware of potential negative implications of soil pollution in certain locations of the settlements and possibly share these with the decision and policy makers.

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Commentary
Kerosene-based lighting: an overlooked source of exposure to household air pollution?

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Access to affordable, reliable, modern and sustainable energy is one of the seventeen Sustainable Development Goals (SDG) set by the United Nations for 2030. However, estimates indicate that progress towards that goal is not on track: 650 million people worldwide are estimated to remain without access to electricity in 2030 (IEA, IRENA, UNSD, WB, WHO, 2019). Nine out of ten of these people will live in Sub-Saharan Africa (SSA), mostly in rural communities, which face barriers in terms of affordability and supply.

Without access to affordable and reliable clean energy to meet daily cooking, lighting, and heating needs, individuals rely on inefficient fuels and technologies that give rise to household air pollution (HAP). Although HAP can arise from several indoor sources, cooking fuels have received most of the attention with respect to global initiatives (e.g. the Global Alliance for Clean Cookstoves supported by the United Nations, https://www.cleancookingalliance.org/) and research-based interventions focused on the health benefits of improved or cleaner cookstoves. Examples of major cookstove interventions conducted in SSA include the Cooking and Pneumonia Study in rural Malawi (Mortimer et al., 2017) and the Rwanda site within the multi-country HAPIN trial of liquefied petroleum gas (Clasen et al., 2020). However, kerosene-based lighting remains a prevalent source of HAP in SSA; estimates indicate that it is used by more than half of households without a connection to the electrical grid (Bensch et al., 2017), particularly in East African countries.

Kerosene lamp emissions contain many health-damaging pollutants (Lam et al., 2012). Use of kerosene lamps has been linked with increased risk of infectious diseases, including tuberculosis (Pokhrel et al., 2010) and acute respiratory infection in children (Barron and Torero, 2017) as well as other safety hazards (e.g. burns, poisonings). Beyond concerns for human health, kerosene lamps are also of concern for their climate impacts. Kerosene lamps have been estimated to emit an average of 25 g of climate warming black carbon per kg of fuel burned (Pfotenhauer et al., 2019).

While HAP exposure from biomass-fuelled cookstoves is an obvious health concern, several aspects of kerosene-based lighting warrant more attention than it has so far received. Portable kerosene lamps tend to be kept very near to users for prolonged periods, resulting in high levels of inhaled pollutants (i.e. more mass inhaled per mass emitted). An experimental study in Kenya estimated that night kiosk vendors can inhale 1560 µg of fine particles per day emitted by kerosene lamps alone (Apple et al., 2010). Relatively few studies have attempted to quantify the contribution of kerosene-based lighting to particle exposure in populations in SSA. We previously reported that kerosene-based lighting was the strongest determinant of 24-h average and peak personal exposure to black carbon among women living in a semi-rural area of Mozambique (Curto et al., 2019). Women who used kerosene as the primary source of lighting had 81% and 93% higher average and peak personal black carbon exposure, respectively, than those using electricity.

Fuel-based lighting is also a potentially attractive target for HAP interventions. First, it has a high exposure reduction potential. Lam and colleagues provided three pico-solar lamps to non-electrified households mainly using kerosene lamps, and three-four weeks later, the 48-h personal exposure to fine particles in adults and school children living in the household was reduced by 52-73% (Lam et al., 2018). Second, in contrast with cookstove interventions, lighting interventions may be more feasible to implement and to have fewer socio-cultural barriers to adoption and sustained use. For example, solar-powered technology such as pico-solar lamps are easily distributed and have had high social acceptability in rural communities mainly because they are convenient, provide brighter light than kerosene, and are linked to cost savings, as they reduce or eliminate expenditure on kerosene. Although the main purpose of pico-solar products is the provision of light, some models of pico-solar lamps include a USB port for mobile phone charging, which incentivizes uptake among off-grid households who can avoid mobile phone charging fees.

The transition from fuel-based lighting to clean technologies is already under way in much of SSA, largely driven by economic development. Although the extent of penetration of clean lighting technology remains uncertain mostly due to population growth and barriers to market consolidation (Lighting Global, WB, GOGLA, ESMAP, 2020). Nonetheless, there is important scope for policies and programs for accelerating this transition, which would likely lead to important health and environmental benefits. For example, shifting subsidies from kerosene fuel to pico and household solar products should be prioritized.

There is a clear need for better quantification of the exposure reduction potential and potential health benefits that could be expected from this transition. High quality research studies on this topic would be of great value to develop evidence to inform effective strategies to accelerate adoption of clean lighting technology and remove barriers. Such evidence can support progress to meeting the SDG goals and to create more healthy, sustainable, and climate-resilient communities.

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Research brief

Quantifying the effect of air quality offsets on household air pollution and thermal comfort on the South Africa Highveld

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South Africa, like other developing countries, has been facing air quality challenges. As a highly industrialised country, industrial emissions both from power generations and mining activities contribute significantly to ambient air pollution. Other sources of emissions come from the agricultural sector (including dust and biomass burning) and veld fires, especially during winter and spring. In both small and large townships, the major source of air pollution is domestic solid fuel burning both for cooking and space warming. Air quality management, therefore, has to struggle with the complex mix of these sources of emissions.

On the regional scale, emissions from industrial and agricultural sectors pose greater challenges than domestic combustion, but on the local scale, the reverse is the case. Research has shown that air pollution is linked to adverse effects on human health. In particular, particulate matter (PM) is said to be highly detrimental to health. PM is a major pollutant from residential fuel burning. There is widespread use of residential solid fuel burning on the South Africa Highveld contributing significantly to ambient air pollution.

When the Department of Environmental Affairs (DEA) published guidelines for air quality offsets, residential fuel burning was one of the main challenges addressed. To test the effectiveness of air quality offset programs, pilot studies were carried out in the densely populated low-income areas on the Highveld. Eskom conducted such a pilot study in Kwazamokuhle, a low-income community situated near three coal-fired plants in Mpumalanga.

To better understand the impact of indoor and ambient PM concentrations as a result of solid fuel burning, this follow up study was conducted to (i) understand the temporal variation of PM concentrations with respect to the meteorology of the location (ii) explore the relationship between indoor and outdoor air quality (iii) comprehend the processes, activities and energy usage patterns that affect the local air quality.

The study, which was carried out during summer and winter, made use of two formal reconstruction and development programme (RDP) houses classified as solid fuel burning (SFB) and non-solid fuel burning (NSFB). The NSFB house has wall and ceiling insulation. It depends on electricity as the major source of energy for cooking and space heating. The SFB house has no insulation and depends solely on solid fuel burning for cooking and space heating. PM_4 continuous measurements were carried out indoors and outdoors at both houses in summer and winter. PM_4 has been shown previously to approximate $PM_{2.5}$.

The study revealed that the daily mean indoor PM_4 concentrations range between 60.9 µg/m^3 and 207.5 µg/m^3 at the SFB house, while the range was 15.3 µg/m^3 to 84.2 µg/m^3 at the NSFB house during the winter. During the summer, the range was between 17.4 µg/m^3 and 36.6 µg/m^3 at the SFB house, and between 14.2 µg/m^3 and 39.9 µg/m^3 at the NSFB house. The daily mean concentrations exceeded the National Ambient Air Quality Standard (NAAQS) 24-hour $PM_{2.5}$ limit of 40 µg/m^3 on some of the days during the winter at the NSFB house but on all the days at the SFB house. No cases of exceedance of the $PM_{2.5}$ daily limit were recorded during the summer at either house. During some days in the winter, the indoor PM_4 concentration at the SFB house went as high as six times that of the NSFB. As to the mean hourly PM_4 concentration, the maximum indoor concentration at the NSFB was about 200 µg/m^3, while that at the SFB house was well above 1200 µg/m^3. This high concentration is very common for the cooking and space heating hours, especially in the evenings. When a comparison is made of the indoor to outdoor diurnal concentrations during winter, the average outdoor concentration was about half that of the indoor concentration. While there were good correlations between the indoor and outdoor PM_4 concentration during the summer, the correlations were very poor during the winter at both houses. This may be as a result of the closing of major house ventilations apart from the chimney in order to aid space heating.

A very important deduction from the indoor to outdoor PM_4 concentration relationship is that the elevated value during the winter is mostly due to the solid fuel combustion and not from the power plants in proximity to the community. The study also has shown that the air quality offset programme, if fully implemented, can be of tremendous benefit to the community in terms of reducing household PM concentration and improving thermal comfort especially during the winter season.

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Research article

Characterisation of semi-volatile hydrocarbon emissions from diesel engines

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Abstract

Exhaust emissions from diesel vehicles have recently been receiving global attention, due to potential human health effects associated with exposure to emitted pollutants. In addition, a link has recently been established between unburnt hydrocarbon (HC) emissions from diesel engines and photochemical smog. Despite being present at very low concentrations in the exhaust, these HCs may act as precursors in the formation of photochemical smog pollution. While short-chain HCs are easier to characterise and have been successfully reduced in many developed cities, longer chain HCs, most likely arising from diesel exhaust emissions, have been poorly quantified to date, and a limited range of HCs from this source has been studied. In this study, transient cycle tests were conducted to collect exhaust emissions from a Euro 3 compliant, 1.6 L test engine fuelled with three diesel fuels; a highly paraffinic fuel, a South African market fuel and a European reference fuel. Portable denuder samplers were used to collect the emissions and analysis was done by thermal desorption-comprehensive 2D gas chromatography-time of flight mass spectrometry (TD-GC x GC-TofMS). The South African market diesel had the greatest n-alkane emissions, with greater emissions observed in the earlier phases (low and medium phase) of the WLTC test cycle. The total n-alkane emissions for this fuel ranged from 34.80 mg/km - 282.67 mg/km from the low to the extra-high phase. The paraffinic diesel had the second highest n-alkane emissions with the total emissions ranging from 35.43 mg/km – 164.99 mg/km. The European reference diesel had the lowest n-alkane emissions amongst the three fuels, with the total emissions ranging from 22.46 mg/km – 82.56 mg/km. Substituted alkyl-benzenes were also detected in the gas phase emissions from each fuel, however only semi-quantitative analysis of these compounds was conducted. The results showed that long-chain HCs were present at easily detectable concentrations in diesel engine exhaust emissions, which is critical in understanding their contribution to photochemical ozone and informing appropriate mitigation and management strategies.

Keywords

Photochemical smog, hydrocarbons, ozone, diesel exhaust emissions, ozone formation potential, emission factor

Introduction

Exhaust fumes from vehicular emissions are one of the biggest contributors to pollution of the ambient atmosphere, which could be of great concern for South Africa's agricultural sector and in urban environments. Photochemical smog is produced in the atmosphere from the reaction of nitrogen oxides (NO_x) and volatile organic compounds (VOCs), in the presence of ultraviolet sunlight. This complex process occurs in the lower atmosphere (troposphere) and results in the formation of photochemical ozone (O_3), the principal component associated with photochemical smog. The Southern African region is characterised by numerous sources of ozone-forming compounds and presents ideal environmental conditions for O_3 formation. The most significant pollutants from vehicular emissions include nitrogen oxides (NO_x) and HCs which are key precursors to photochemical smog formation. Whilst both diesel and petrol engines contribute to NO_x emissions, until recently the latter was thought to be the primary source of HC emissions in the atmosphere. Characterisation studies on airborne organic compounds in the USA show that there is a significant contribution of semi-volatile organic compounds (SVOCs) emanating from diesel exhaust, to the atmosphere's non-methane organic gas (NMOG) load (Jathar et al., 2014). Gaseous diesel exhaust HCs are composed predominantly of alkanes (straight, branched and cycloalkanes), aromatics (alkyl-benzenes and 2-5 ring polycyclic aromatic hydrocarbons) and alkenes (Gentner et al., 2012, Storey et al., 1999). Although the South African vehicle fleet is dominated by petrol cars, the National Association of Automobile Manufacturers of South Africa (NAAMSA) has reported a steady increase in the popularity of diesel engine models over recent years (Energy, 2017).

SVOCs are described as compounds with an effective saturation concentration (C*) of 0.1 µg m^{-3} – 1000 µg m^{-3} which corresponds to a vapour pressure range of 10^{-8}-10^{-2} Torr (Robinson et al., 2007). These compounds tend to partition between the particulate and gaseous phases at high atmospheric dilution, and thus may participate in gas phase photochemical reactions.

Numerous studies have reported that long term exposure to PM emissions may cause cardiovascular and respiratory diseases, whilst the organic compounds adsorbed onto the surface of PM are toxic and carcinogenic (Reşitoğlu et al., 2015, Kagawa, 2002, Wichmann, 2007). The detrimental health and environmental impacts of photochemical O_3 such as eye irritation, a decline in respiratory function, reduced visibility and damage to crops and vegetation (Laban et al., 2018) has also been reported in literature. According to the South African National Ambient Air Quality Standards for Criteria pollutants (2009 and 2012), the 8-hourly running average standard for O_3 is 120 µg/m^3 (61 ppb), however numerous exceedances have been observed in various regions in South Africa. A study by Zunckel et al. monitored surface ozone outside urban areas in Southern Africa and found that the highest O_3 concentrations were over Botswana and the Mpumalanga Highveld (Zunckel et al., 2004). Both regions had highs between 40 and 60 ppb, however the average concentration in October 2000 was greater than 90 ppb. Gautam et al. speciated diesel exhaust emissions under steady state conditions (Gautam et al., 1996). The ozone formation potential (OFP) of speciated alkyl-benzenes ranged from 0.406 - 0.767 mg O_3/bhp-hr for ethylbenzene and 1,2,4-trimethylbenzene respectively and OFP values of 0.119 mg/bhp-hr and 0.018 mg/bhp-hr were reported for octane and nonane respectively, where bhp-hr is brake horsepower-hour. In another study by Olumayede, the contribution of individual VOCs to photochemical ozone formation in Southern Nigeria was studied (Olumayede, 2014). The following photochemical O_3 formation potentials were reported: 25.7 µg/m^3 for m,p-xylene, 11.02 µg/m^3 for ethylbenzene, 26.43 µg/m^3 for undecane, 18.85 µg/m^3 for 1,2,4-trimethylbenzene and 12.27 µg/m^3 for toluene. It is evident that the contribution of different HC species to O_3 formation varies within chemical classes and between HCs of different classes.

Detailed mechanisms underlying the photochemical conversion of precursor compounds to photochemical ozone have not been elucidated, however, the key elements can be explained using generalized reaction mechanisms. Smog chamber irradiation studies have also been conducted to investigate ozone formation as a function of the initial concentration of its precursors. These studies show that reducing HC and NO_x concentrations simultaneously leads to a decrease in O_3, however, this is less than the decrease observed from HC reduction alone (Glasson, 1981). Thus historically it has been known that by controlling HC levels in the atmosphere, O_3 reduction could be achieved in urban areas (Glasson, 1981). In recent years, VOC emissions have been successfully quantified and reduced in many developed cities, however, research shows that longer chain HCs are typically not considered as part of air quality control strategies. A study was conducted using high resolution measurements to investigate the abundance of diesel related HCs in the atmosphere at an urban background site in London and a comparison of these results to the emission inventory data showed that there is a drastic underestimation of the impact of diesel related emissions on urban air quality (Dunmore et al., 2015).

The challenge faced when characterising SVOCs stems from difficulties in quantitative collection and chemical analysis of these species. Traditional sampling methods for gaseous-particulate phase analytes employ high volume samplers that make use of a glass fibre filter that removes particles from the sample flow, and an adsorbent such as Tenax or polyurethane foam (PUF), to adsorb the gas phase analytes downstream of the filter (Geldenhuys et al., 2015). Although such high volume samplers are robust and easy to use in the field, they exhibit inherent limitations due to the sampling configuration and high volumetric flow rate (Forbes and Rohwer, 2015). Another commonly used sampling method, particularly when conducting engine tests, is collection of dilute exhaust emissions into Tedlar® bags from a constant volume sampler (CVS) and subsequent analysis of emissions by gas chromatography-mass spectrometry (GC-MS). This sampling method is adequate for sampling of VOCs, however, heavier compounds tend to condense on the walls of the sampling bags, which results in errors during quantitative analyses (Newkirk et al., 1993).

Denudation, a sampling technique that has been used extensively for air monitoring applications, eliminates two major limitations suffered by high volume samplers. By removing SVOC gas phase analytes prior to downstream collection of the particulate matter, it prevents adsorption of the gas phase analytes onto particulate matter collected on the filter or onto the filter medium itself. The second artefact relates to volatilisation of the particle phase analyte from the filter. During denudation, a second gas phase sampling device is placed downstream of the filter, which collects any "blow-off" from the filter (Forbes and Rohwer, 2015). Furthermore, denuders allow for collection of diluted exhaust samples, without the need to collect large volumes of samples, as analytes are stripped from the air sample and pre-concentrated onto the sorbent, which later may be extracted or introduced directly into the analytical instrument during analysis.

In this study, an emissions monitoring campaign was conducted to collect and characterise diesel exhaust emissions from a diesel test engine which is a popular model for the passenger car fleet on South African roads. Simulated vehicle exhaust emission testing was conducted at a controlled engine test cell facility using a standard emission test cycle. Cold-start emission tests were performed for three different fuels. Simultaneous sampling of gaseous and particulate exhaust emissions was achieved by using denuder sampling devices with thermal desorption-comprehensive two dimensional gas chromatography-time of flight mass spectrometry (TD-GC x GC-TofMS) analysis. Here we report on these gas phase n-alkane and aromatic hydrocarbon diesel emissions and their related ozone formation potentials which can be estimated by assigning maximum incremental reactivity (MIR) indices to each compound.

Experimental

Test engine and Test fuels

Simulated vehicle emissions testing was conducted in a test cell (Fig 1) with a Euro 3 compliant, 1.6 L test engine, which was fitted with a close-coupled diesel oxidation catalyst (DOC).

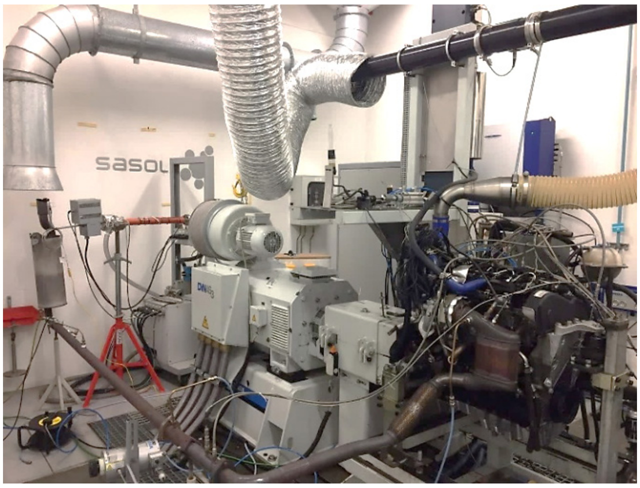

Figure 1: *Test cell setup*

The engine had completed ~137 hours of running on the test bed, under varied operating conditions. A complete set of diagnostic checks were carried out on the engine before testing commenced to ensure that it was performing according to specification. The test engine was coupled to an electrical engine dynamometer which uses a mathematical model to simulate engine operation during emissions testing. Figure 1 shows the test cell setup. Three diesel fuels were selected for testing: a highly paraffinic diesel fuel complying with the European EN15940 specification (PAR10), a South African market fuel complying with the South African SANS 342 specification (SAM10), and a reference fuel complying with the European EN590 specification (EUR10). All of the fuels contained less than 10 ppm sulphur, and were chosen because of their distinct compositional characteristics. The dynamometer details and fuel specifications are listed in Table 1 and Table 2 respectively.

Table 1: *Dynamometer details*

Make and model	Horiba Dynas3 LI350
Rated power and torque	350 kW, 750 Nm
Control system	Horiba SPARC controller and Horiba STARS test automation system

Test cycle

The World Harmonized Light vehicle Test Cycle (WLTC) was used for emissions testing. Figure 2 illustrates a typical speed profile of this test cycle. It consists of four characteristic speed phases (low, medium, high and extra high), and emissions from each phase were collected onto separate samplers.

Table 2: *Fuel properties and composition*

Analysis	Method	Sasol 10ppm	EN590	GTL
Sulfur, mg/kg	ASTM D5453	5	<1	<1
Density, kg/l @ 20 °C	ASTM D4052	0.8163	0.8328	0.7650
Flash Point, °C	ASTM D93	63.9	83.0	57.0
Distillation, °C	ASTM D86			
Initial Boiling Point		176.8	193.1	150.6
5%		187.0	207.1	173.9
10%		192.4	218.1	184.3
50%		232.8	277.0	262.8
90%		333.5	333.0	338.6
95%		368.2	347.9	352.4
Final Boiling Point		389.1	355.6	356.7
Cetane number	ASTM D6890	49.7	53.8	80.0
Viscosity, cSt @ 40°C	ASTM D445/D7042	2.06	2.79	2.20
N-paraffins	GC X GC (mass %)	24.5	9.4	51.9
Branched paraffins		24.1	39.9	47.7
Monocyclic Paraffins		14.0	16.8	0.2
Bi-and polycyclic paraffins		9.2	4.7	0.2
Alkyl benzenes		10.9	13.2	0.0
Cyclic alkylbenzenes		14.9	9.1	0.0
Bi- and polycyclic aromatics		2.3	6.9	0.0
Sum		99.9	100.0	100.0

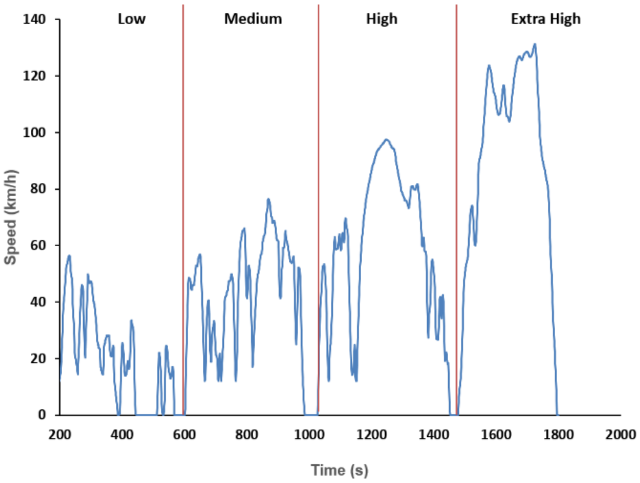

Figure 2: *Speed profile of the WLTC test cycle used during emissions testing.*

Emissions sampling and instrumental analysis

Exhaust gas was drawn directly from the engine's exhaust pipe and fed into a mini dilution tunnel (Horiba MDLT-1303T). The diluted exhaust was sampled onto denuder samplers consisting of a quartz fibre filter sandwiched between two multi-channel polydimethylsiloxane (PDMS) traps (Forbes et al., 2012) via a four-way flow splitter at the exit of the dilution system. Portable sampling pumps (GilAir plus, Sensidyne) were used to draw the diluted exhaust through the denuders at a sampling rate of 500 mL/min. Samples were collected in duplicate for each fuel after which the test fuel was changed.

During fuel change-over the fuel supply system was flushed with approximately 10 litres of the new fuel to remove the remaining old fuel. This was then followed by a 60 min run where the engine was operated at mid-load conditions (50% of full load), at 2500 rpm for an hour. The engine was then pre-conditioned with the new fuel by running the test cycle once, followed by a 20 min run at mid-load conditions, at 2500 rpm once again. The engine was then shut down, and left un-operated overnight, allowing it to stabilize to ambient temperature.

After sampling, each PDMS trap was end capped, wrapped in Al foil and each quartz fibre filter was placed in a clean amber vial. Samples were placed in zip lock bags and refrigerated at -18 °C until analysis using a LECO Pegasus 4D TD-GC x GC-TofMS system with an internal standard mix containing hexadecane-d34, naphthalene-d8 and phenanthrene-d10 in hexane.

Hydrocarbon speciation

Identification of target aromatic and alkane HCs was achieved by matching retention times to those of authentic reference standards (C8-C20 n-alkane standard from Sigma-Aldrich and DHA-aromatic standard from Restek) and calculated retention indices, as well as mass spectral matching using the NIST MS search mass spectral library. Quantitation of n-alkane HCs was achieved by linear regression analysis. Six concentrations (1, 5, 10, 20, 30 and 60 ng/µL) of the C8-C20 alkane standard mix were prepared in hexane (99%, Sigma-Aldrich) and each standard was spiked onto a pre-conditioned trap and analysed in duplicate on the TD-GC x GC-TofMS.

To calculate the emission factor (ng/km) of each n-alkane the mass obtained from calibration (ng) was corrected using dilution factors which were measured continuously during emissions testing.

Results and Discussion

N-alkane gas phase emissions

Transient cycle tests were performed for all three fuels from a cold engine start, over each phase of the WLTC test. Figure 3 shows the relative n-alkane emission factors of each fuel for each phase of the WLTC cycle. The SAM10 diesel had the greatest n-alkane emissions with greater emissions observed in the low phase of the WLTC cycle, and PAR10 diesel had the second highest n-alkane emissions. The EUR10 diesel had the lowest n-alkane emissions amongst the three fuels which may be attributed to its low n-paraffin fuel content, and, potentially its lower volatility. Although PAR10 diesel has the highest n-paraffin fuel content, it had lower n-alkane emissions than the SAM10 diesel. This could be as a result of the high cetane number of this fuel compared to that of the SAM10 fuel. A higher cetane number means the fuel ignites easily which results in better fuel combustion and thus reduction of harmful emissions from unburnt HCs (Ladommatos et al., 1996). A correlation between HC emissions and cetane number has been demonstrated for diesel engine emissions where a reduction in HC emissions was observed with increasing cetane number (Bartlett et al., 1992).

From Figure 3, although unexpectedly higher emissions were observed during the high phase of the WLTC cycle, a general decrease in emissions was observed from the “Low” phase to the “Extra high” phase. This is a result of an increase in the engine and exhaust catalyst temperature which results in improved combustion conditions and catalytic oxidation during engine operation.

Aromatic hydrocarbon gas phase emissions

Semiquantitative analysis of the test fuel emissions was also conducted to identify target aromatic HCs. The target list contained 30 alkyl-benzenes. Figure 4 shows the relative gas phase alkyl-benzene emission factors of each fuel for each phase of the WLTC cycle. It is evident that the EUR10 fuel had the highest alkyl-benzene hydrocarbon emissions, followed by the SAM10 fuel and PAR10 fuel respectively. This trend was highly consistent with the fuel composition, as the EUR10 fuel has the highest alkyl-benzene fuel content and the SAM10 fuel the second highest.

Alkyl-benzene emissions were seen for the PAR10 fuel, although this fuel contains no alkyl-benzenes, thus emissions were suspected to be from residual alkyl-benzene emissions from the previous combustion of other fuels. To further investigate this, a

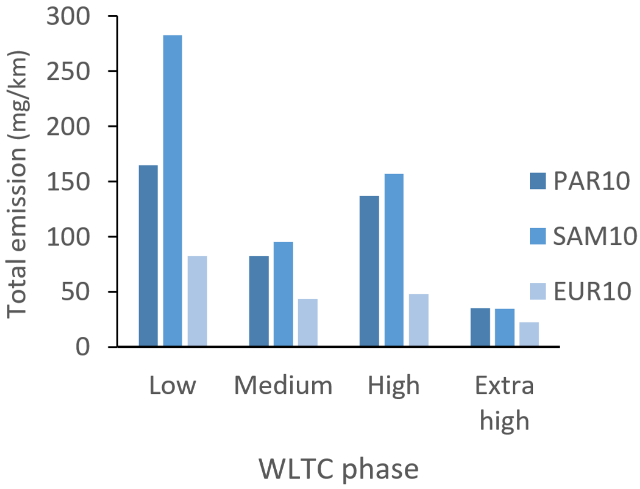

Figure 3: Relative gas phase n-alkane cold start emissions summed up for each of the WLTC test cycle phases, for each test fuel.

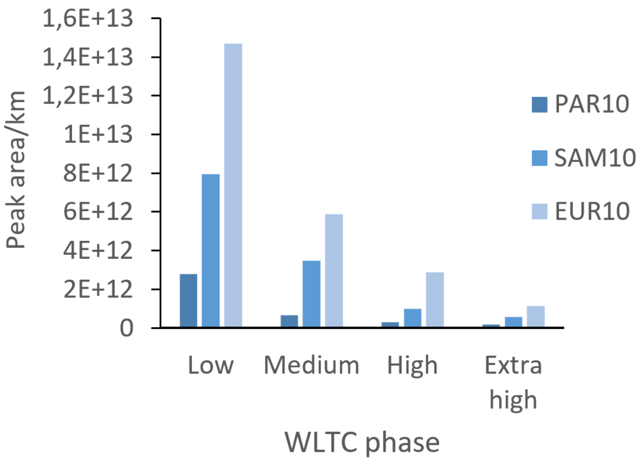

Figure 4: Relative gas phase alkyl-benzene cold start emissions summed up for each of the WLTC test cycle phases, for each test fuel.

qualitative analysis of the background samples was conducted. Background samples were taken with the engine switched off, however, the dilution ratio was kept constant to maintain the volume of incoming dilution air. Analysis of these samples confirmed that most of the target alkyl-benzenes were present at low levels in the background air.

Figure 5 shows a comparison of the peak areas of alkyl-benzenes identified in the emissions of the SAM10 fuel as compared to the background air.

Similar compounds to the ones reported in this study were found by other diesel exhaust characterisation studies (Alves et al., 2015, Gentner et al., 2013, Schauer et al., 1999). Comparing the emission factors however can be challenging as the emission factors of hydrocarbons from mobile sources have been shown to depend on engine design, engine operation and fuel composition (Cross et al., 2015), amongst other factors.

Effect of the exhaust after-treatment systems

To meet the increasingly stringent air quality limits regarding

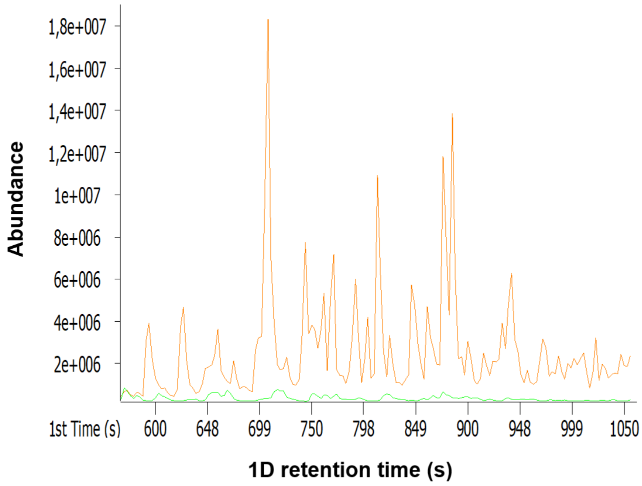

Figure 5: Example extracted ion chromatograms (m/z = 91) showing the gas phase aromatic hydrocarbon emissions from SAM10 diesel cold start Phase 1 (top) as compared to the background air (bottom).

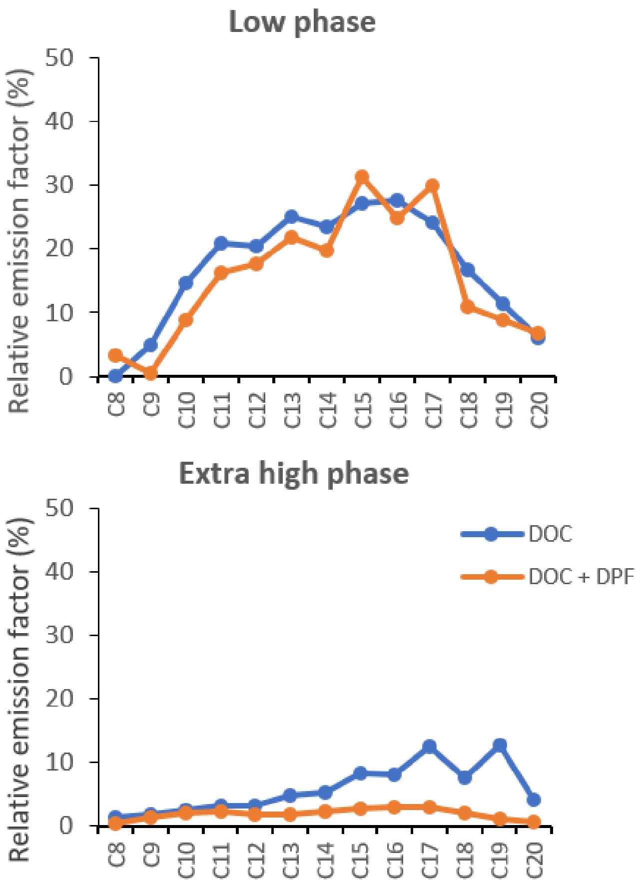

Figure 6: Preliminary relative gaseous n-alkane emission factors for the DOC and DOC+DPF exhaust after-treatment configurations.

vehicular exhaust emissions, modern day diesel vehicles have exhaust after-treatment systems, which may include a diesel oxidation catalyst (DOC), diesel particulate filter (DPF) and/or a selective catalytic reduction (SCR) system. To investigate the effect of the exhaust after-treatment system, emissions tests were performed using two configurations: DOC and DOC-DPF. Figure 6 shows the n-alkane relative emission factors for both configurations, during the low phase of the WLTC cycle.

Figure 7: *Quartz fibre filters used to collect particulate emissions for the EUR10 fuel during the low phase of the WLTC test cycle with the DOC only (left) and the DOC-DPF (right) in-line.*

The relative emission factors (%) were determined by expressing the emission factor of each n-alkane relative to that of the n-alkane with the highest emission factor (≡100). The results show a decrease in emissions from the low phase to the extra-high phase, which can be attributed to oxidation of gaseous hydrocarbon emissions by the DOC during high engine temperatures. The results also show lower emissions for the DOC-DPF configuration as compared to the DOC configuration. This was attributed to additional oxidation of HCs by precious metals found within the DPF as well as removal of hydrocarbons adsorbed onto the surface of particulate matter by the DPF.

Figure 7 shows the effective removal of soot and PM by the DPF. These results show the importance of the exhaust after-treatment system, however, the issue remains that optimum functioning of the DOC and regeneration of the DPF requires high engine temperatures which are seldom reached during low-speed city driving conditions.

Ozone formation potentials

The OFPs of the hydrocarbon emissions can be estimated using Carter's MIR indices which give the impact of each compound to the peak ozone concentration in a system where ozone is being formed under high NO_x concentrations, and is most sensitive to HC emissions (Carter 2010). The MIR index of each compound is given as the mass of additional ozone formed per mass of compound added to the emissions (gO_3/gVOC). Thus using the emission factors, the OFP of each compound can then be determined from the product of the emission factor (EFn) and MIR index (MIRn) of each alkane, where n refers to the alkane with n number of carbons (equation 1).

$$OFP[gO_3/km] = EFn\,[gVOC/km] \times MIRn\,[gO_3/gVOC] \quad (1)$$

Photochemical smog occurs predominantly in urban areas, thus phases 1 and 2 (low and medium) cold start emissions were chosen to study the OFP of the different fuels, as they consist of low speeds which are characteristic of urban driving conditions.

The photochemical smog formation potential of n-alkane emissions from each fuel differed. A comparison of the fuel emissions revealed that the SAM10 fuel emitted more ozone forming n-alkane and aromatic HC emissions than the other two fuels. EUR10 diesel had the least n-alkane emissions, however, it had relatively high aromatic HC emissions, which contributed to the OFP of this fuel, as these compounds have large MIR indices. The PAR10 fuel had relatively high n-alkane emissions, which have low MIR factors, although high emission factors would contribute to the OFP of this fuel.

From these results, it is evident that SVOCs arising from diesel emissions have the potential to contribute to photochemical ozone formation in the atmosphere, especially in urban traffic dense areas. The comparison between the test fuels cannot be regarded as conclusive, however, as diesel fuels also contain significant concentrations of branched and cyclic paraffins, which were not quantified in this study.

Conclusion

SVOC exhaust emissions from a diesel engine used in light-duty passenger vehicles were characterised for three fuels. The engine was operated over the WLTC driving cycle consisting of low, medium, high, and extra high speed phases. HC (n-alkane and aromatic) gas phase emissions arising from each fuel were then determined for each phase of the test cycle. The three test fuels showed differing levels of n-alkane and aromatic SVOC emissions, and hence their OFP differed, which could tentatively be explained by the physical and chemical characteristics of the fuels. A general decrease in n-alkane emissions was observed for each fuel when moving from the "Low" to the "Extra high" speed phase of the test cycle, and lower gas phase hydrocarbon emissions were observed in the presence of a DOC and DPF combination. This was attributed to increased engine temperatures which result in improved combustion conditions and optimal functioning of the DOC and DPF. Monitoring of semi-volatile HC emissions may be critical in understanding elevated ozone levels in urban areas, which are often higher than model predictions. This study has illustrated the successful use of denuders and comprehensive 2D gas chromatography with mass spectrometric detection to collect and characterise semi-volatile n-alkane and aromatic emissions from diesel exhaust. Such studies are important in better understanding the tropospheric ozone levels in South Africa and in informing air quality management practices.

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Research article

Evaluating the potential of remote sensing imagery in mapping ground-level fine particulate matter ($PM_{2.5}$) for the Vaal Triangle Priority Area

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Abstract

The quality of air breathed in South Africa is of great concern, especially in industrialised regions where $PM_{2.5}$ concentrations are high. Long term exposure to $PM_{2.5}$ is associated with serious adverse health impacts. Traditionally, $PM_{2.5}$ is monitored by a network of ground-based instruments. However, the coverage of monitoring networks in South Africa is not dense enough to fully capture the spatial variability of $PM_{2.5}$ concentrations. This study explored whether satellite remote sensing could offer a viable alternative to ground-based monitoring. Using an eight-year record (2009 to 2016) of satellite retrievals (MODIS, MISR and SeaWIFS) for $PM_{2.5}$ concentrations, spatial variations and temporal trends for $PM_{2.5}$ were evaluated for the Vaal Triangle Airshed Priority Area (VTAPA). Results were compared to corresponding measurements from the VTAPA surface monitoring stations. High $PM_{2.5}$ concentrations were clustered around the centre and towards the south-west of the VTAPA over the highly industrialised cities of Vanderbijlpark and Sasolburg. Satellite retrievals tended to overestimate $PM_{2.5}$ concentrations. Overall, there was a poor agreement between satellite-retrieved $PM_{2.5}$ estimates and ground-level $PM_{2.5}$ measurements. Root mean square error values ranged from 6 to 11 µg/m^3 and from -0.89 to 0.32 for the correlation coefficient. For satellite remote sensing to be effectively exploited for air quality assessments in the VTAPA and elsewhere, further research to improve the precision and accuracy of satellite-retrieved $PM_{2.5}$ is required.

Keywords

Satellite retrievals, ground-based data, $PM_{2.5}$ concentration, spatial variations

Introduction

At a global scale, air pollution is ranked fourth amongst the leading risk factors to human health, with recent estimates linking it to over 5 million premature deaths (Mannucci and Franchini, 2017; Bhanarkar et al., 2018; Health Effects Institute, 2019). In sub-Saharan Africa (SSA), particularly in the urban areas, the deterioration in air quality as a result of rapid urbanisation, population growth and industrial expansion is evident (Amegah and Agyei-Mensah, 2017; Fayiga, Ipinmoroti and Chirenje, 2018). Of great concern to public health, are the levels of fine particulate matter ($PM_{2.5}$) in the cities of SSA, which are amongst the highest in the world (Fayiga, Ipinmoroti and Chirenje, 2018; Katoto et al., 2019). Long-term exposure to high levels of $PM_{2.5}$ is harmful to humans as it can lead to increased severity in the symptoms of asthma and chronic obstructive pulmonary disease (Dieme et al., 2012; Feng et al., 2016).

In South Africa, air pollution has become an important issue, especially in industrialised regions like the Vaal Triangle Airshed Priority Area (VTAPA) where strong economic growth has taken place (Naiker et al., 2012; Zhu et al., 2012). The VTAPA routinely experiences poor air quality as a result of strong emissions from industries, residential burning, vehicles and fugitive dust sources coupled with unfavourable meteorological conditions that have led to the accumulation of $PM_{2.5}$ in high concentrations (Annegarn and Scorgie, 1997; Scorgie et al., 2003).

To improve air quality and public health in the VTAPA, the Department of Environmental Affairs (DEA) developed an air quality management plan that outlined strategies to reduce emissions from key sources (Department of Environmental Affairs and Tourism, 2009; Tshehla and Wright, 2019). Furthermore, air quality monitoring stations were placed at identified hotspots in the VTAPA, so as to assess pollution trends and to ascertain whether concentrations of $PM_{2.5}$ and other pollutants are being kept within the regulatory limits (Ngcukana, 2016; Altieri and Keen, 2019). However, similar to other urban areas across the world (Gupta et al., 2006; Tian and Chen, 2010; Hu et al., 2014), the spatial coverage of stationary ambient monitors in the VTAPA is low. Intra-urban variability of $PM_{2.5}$ concentrations is therefore not accounted for. In order to capture the full-scale variability of $PM_{2.5}$ concentrations in the VTAPA, there is need for a vast network of monitoring stations. However, this requires large financial resources (Munir et al., 2016).

Satellite remote sensing can provide repeated observations of atmospheric pollution at large spatial scales. The monitoring of air pollutants using satellite observations is gradually gaining more attention in atmospheric pollution studies (Engel-Cox, Hoff and Haymet, 2004; Duncan et al., 2014). Advancements in regional algorithms have allowed for the large scale retrieval of $PM_{2.5}$ concentrations at fine spatial resolutions that have a reasonable agreement with ground measurements (van Donkelaar et al., 2015; van Donkelaar et al., 2016). These retrievals have been successfully used to assess long term spatial-temporal patterns of $PM_{2.5}$ in regions experiencing poor air quality such as China and Saudi Arabia (Lu et al., 2017; Munir et al., 2016; Shi et al., 2012).

In the case of South Africa, knowledge on the applicability of remote sensing to monitor air pollution levels is insufficient. A regional case study by Kneen et al. (2016) revealed that satellite technology has the potential to offer a practical and credible option to ground-based monitoring in South Africa. However, further investigation is still required in order to have more concrete evidence to advocate the use of remote sensing for air quality monitoring in South Africa. This study evaluated the potential use of remote sensing imagery for air quality assessment in the VTAPA using a publicly available high resolution remotely sensed $PM_{2.5}$ concentration global dataset developed by van Donkelaar et al. (2015). This dataset begins in 1998 and ends in 2016. Spatial variations in satellite-retrieved $PM_{2.5}$ concentrations were examined, and temporal trends were explored.

Methods

Study region

The VTAPA is an industrialised region lying on the South African Highveld, a high central plateau of South Africa that forms part of the grassland biome. It stretches from southern Gauteng down to the northern section of the Free State province with an area of over 4 900 km^2 (Figure 1). The region is host to industries including iron and steel manufacturers (ArcelorMittal steel and Davesteel), ferroalloy (Samancor Metalloys) and petrochemical companies (Sasol Chemical Industries, Natref and Omnia fertilisers). Eskom's Lethabo power station is also located in this region.

The VTAPA has a population of over 3 million people with most of its inhabitants residing in south-western Johannesburg, Soweto, Sebokeng, Sharpeville, Vereeniging, Vanderbijlpark, Sasolburg and Zamdela.

Satellite-derived data

Global satellite-derived $PM_{2.5}$ concentration data with a high spatial resolution (1 km x 1 km) covering a 10-year period from 2007 to 2016 was obtained from the Atmospheric Composition Analysis Group of Dalhousie University (http://fizz.phys.dal.ca/~atmos/martin/). This global dataset was generated by merging satellite

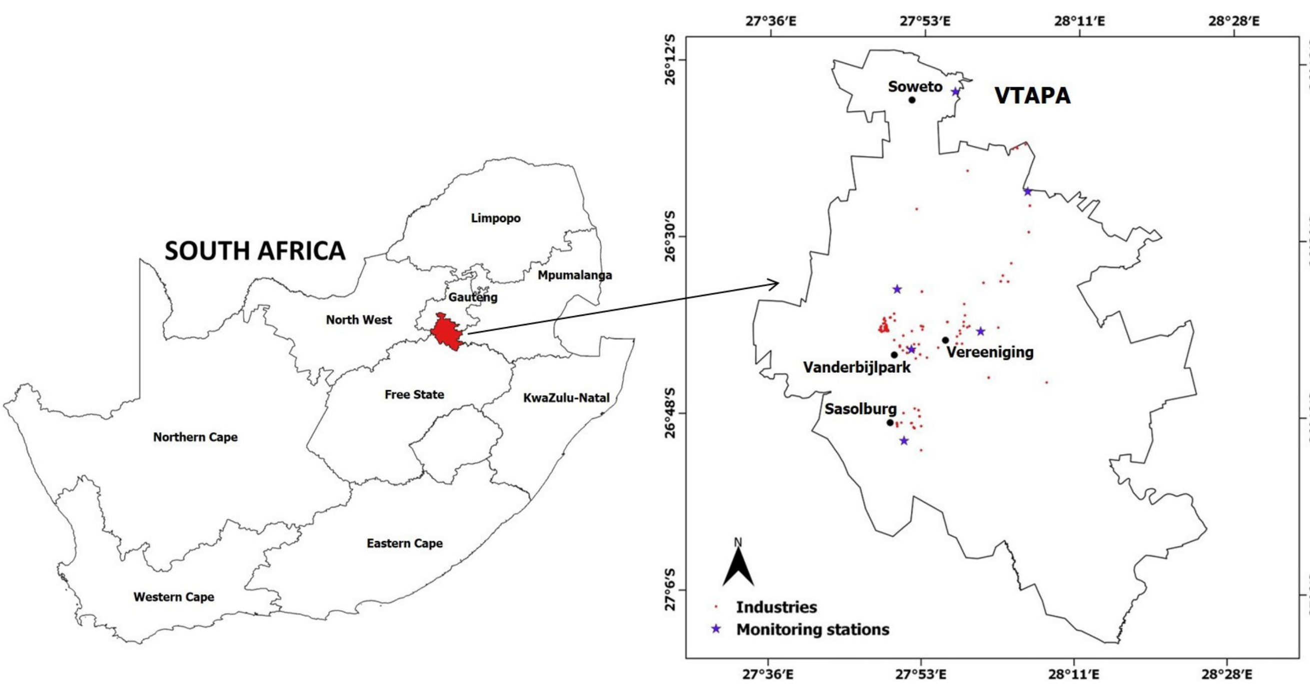

Figure 1: *Study area map showing the location of the VTAPA in South Africa*

retrievals of AOD (Aerosol Optical Depth) from the NASA MODIS (MODerate resolution Imaging Spectroradiometer), MISR (Multi-angle Imaging SpectroRadiometer) and SeaWIFS (Sea-viewing Wide Field-of-view Sensor) instruments with AOD simulated using the GEOS-Chem chemical transport model in order to produce $PM_{2.5}$ estimates (van Donkelaar et al., 2016). The $PM_{2.5}$ estimates were then calibrated by means of a Geographically Weighted Regression (GWR) based on ground observations (van Donkelaar et al., 2015). These estimations have a good agreement with ground-based $PM_{2.5}$ measurements ($R^2 = 0.81$, slope of 0.82).

Based on previous research, uncertainty may exist in the global $PM_{2.5}$ data as a result of the satellite retrieval method (van Donkelaar et al., 2015). Existing studies have resolved this by applying a three-year average as an annual average (Han, Zhou and Li, 2015; Peng et al., 2016; Shisong et al., 2018). For this research, three-year moving averages were applied to the satellite retrievals from the period 2009 to 2016. A subset of the global $PM_{2.5}$ dataset for each year was extracted to cover the VTAPA study area using the Integrated Land and Water Information System (ILWIS) program (ITC, 2011).

Ground measured data

The VTAPA air quality monitoring network consists of six stations (Figure 1), which are located in Diepkloof (26.2507S, 27.9564E), Kliprivier (26.4203S, 28.0849E), Sebokeng (26.5878S, 27.8402E), Sharpeville (26.6898S, 27.8678E), Three Rivers (26.6583S, 27.9982E) and Zamdela (26.8449S, 27.8551E), and have been operational since 2007. Based on the simulated spatial distribution of air pollutants from dispersion modelling these monitoring stations, except for Kliprivier, are considered to be located in high PM_{10} concentration zones (Thomas, 2008; Department of Environmental Affairs and Tourism, 2009; Ngcukana, 2016). $PM_{2.5}$ concentration data (2007–2016) for the VTAPA network was acquired from the South African Air Quality Information System (SAAQIS). This data was quality checked by removing negative values. For consistency with the satellite retrievals, three-year moving averages were also applied to the ground $PM_{2.5}$ concentration data from the period 2009 to 2016.

Results and discussion

Comparison of temporal variations between satellite-retrieved and ground measured $PM_{2.5}$ concentrations

A comparison between satellite-retrieved and ground measured $PM_{2.5}$ concentrations for the six monitoring stations in the VTAPA for the period 2009–2016 is shown in Figure 2. It can be observed that in most cases, there was an overestimation of observed $PM_{2.5}$ concentrations by the satellite retrievals, with the exception for the Kliprivier and Sebokeng stations, where ground measurements were much higher than the satellite-retrieved estimates. Both satellite retrievals and ground measurements showed that $PM_{2.5}$ concentrations for all sites, except Diepkloof, were above the annual National Ambient Air Quality Standards (NAAQS).

Figure 3 shows the 8-year averages for satellite-retrieved and ground observed $PM_{2.5}$ concentrations at all stations. The Sharpeville station had the smallest offsets with a difference of 0.7 µg/m³ between observed measurements and estimates retrieved from satellite imagery. Fairly high offsets were observed for the Sebokeng (-4 µg/m³), Zamdela (5 µg/m³) and Klipriver stations (-6 µg/m³). The performance of the satellite retrieved model was less encouraging for the Diepkloof and Three Rivers stations that both had considerably large offsets of 10 µg/m³.

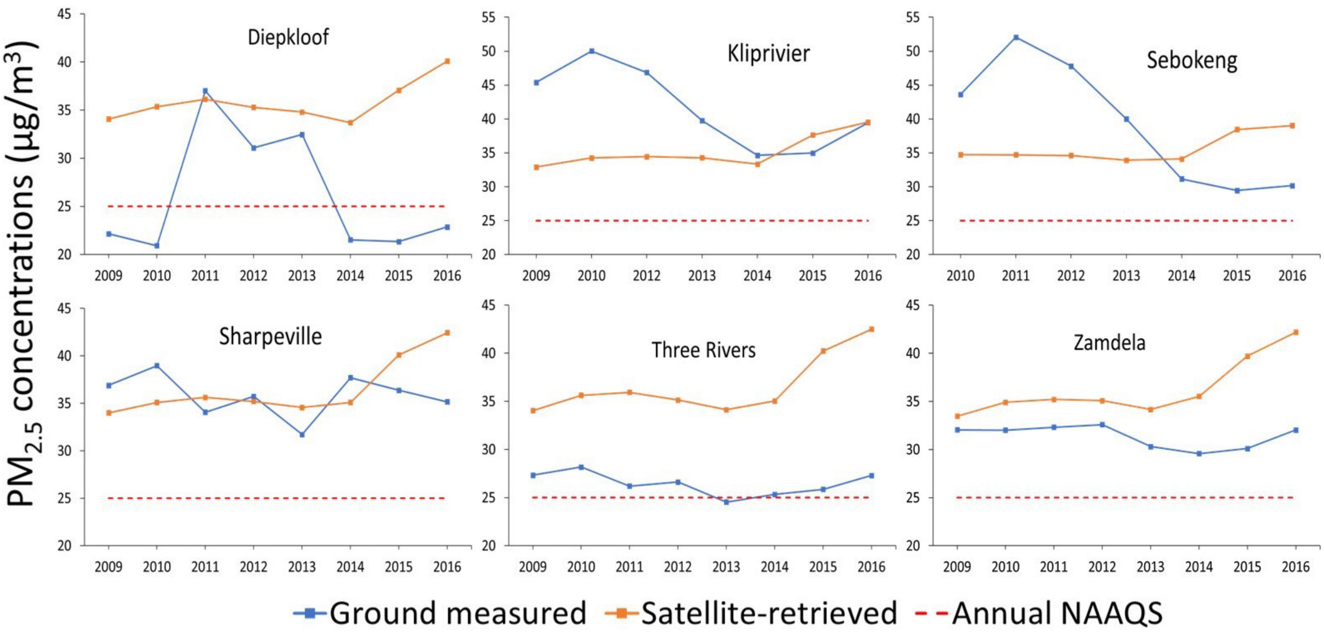

Figure 2: *Comparisons between satellite-retrieved and ground measured $PM_{2.5}$ concentrations at Diepkloof, Kliprivier, Sebokeng, Sharpeville, Three Rivers and Zamdela stations from 2009 to 2016*

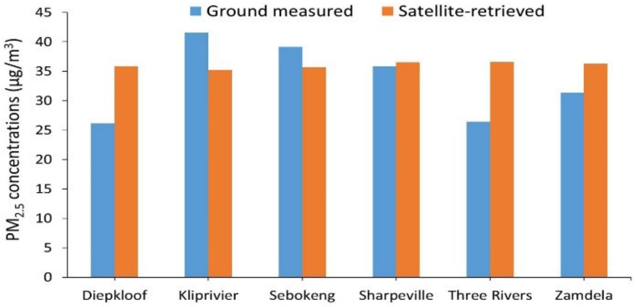

Figure 3: *Comparison of the ground measured and satellite-retrieved 8-year averaged $PM_{2.5}$ concentrations at Diepkloof, Kliprivier, Sebokeng, Sharpeville, Three Rivers and Zamdela stations.*

Table 1: *Comparisons between $PM_{2.5}$ satellite retrieval and ground measurements for the period 2009 – 2016 using RMSE and R statistics.*

Year	RMSE (µg/m³)	R
2009	8	-0.79
2010	10	-0.86
2011	9	-0.70
2012	8	-0.89
2013	6	-0.19
2014	7	0.10
2015	10	0.32
2016	11	-0.04

Satellite retrieval performance evaluation

Satellite retrievals for $PM_{2.5}$ were compared with the ground measurements from all monitoring stations for the period 2009 to 2014 using the following performance evaluation metrics: root mean square error (RMSE) and correlation coefficient (R). These statistics were computed in R statistical software using the modstat function in the Open Air package. RMSE values ranged from 6 to 11 µg/m³, with an average of 9 µg/m³, indicating a significant difference between ground measured and satellite-retrieved $PM_{2.5}$ values (Table 1). R values for the years 2009–2012 ranged from -0.70 to -0.89, demonstrating strong negative correlations between satellite retrievals and ground-based measurements. These inverse relationships, however, do not imply a good agreement between satellite-retrieved $PM_{2.5}$ estimates and ground-level $PM_{2.5}$ measurements. R values from the period 2013 to 2016, displayed weak correlations between ground measured and satellite-retrieved $PM_{2.5}$ concentrations.

Spatial variations of satellite-derived $PM_{2.5}$ concentrations

Variations in annual $PM_{2.5}$ concentrations over the VTAPA from 2009 to 2016 are presented in Figure 4. The average $PM_{2.5}$ concentrations in this region increased significantly by 25% from 33 µg/m³ in 2009 to 41 µg/m³ in 2016. This large increase took place mainly from 2015 to 2016, during which the highest concentrations (41 µg/m³–44 µg/m³) were observed in the VTAPA. The high $PM_{2.5}$ concentrations from 2015 to 2016 could possibly be due to increased AOD resulting from changes in aerosol mass transport during the *El Niño* episodes experienced in South Africa. *El Niño* events can increase regional aerosol concentrations by

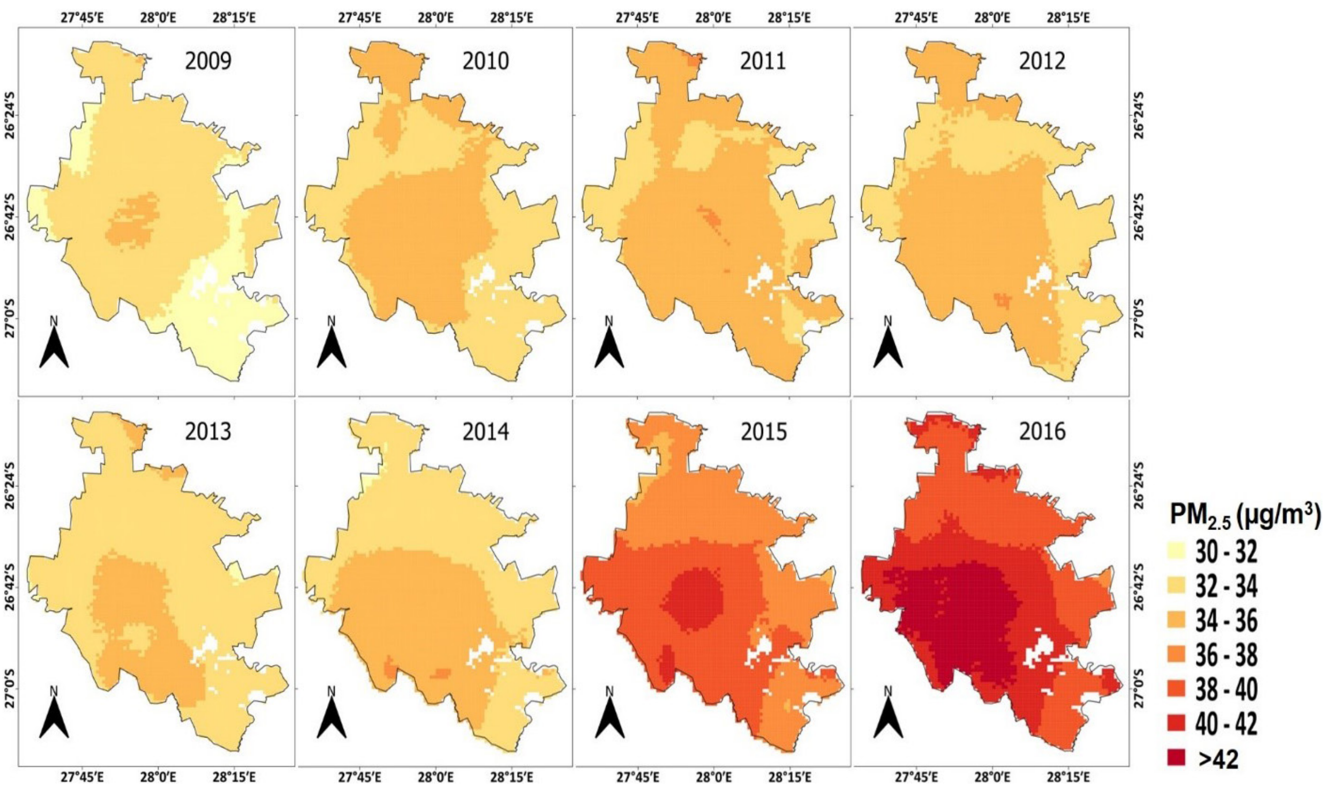

Figure 4: *Spatial distributions of annual $PM_{2.5}$ concentrations in the VTAPA from 2009 to 2016.*

altering atmospheric circulation systems which leads to changes in the transport and removal of aerosols (Yu et al., 2019). Wang et al., (2019) found a positive link between the *El Niño* Southern Oscillation (ENSO) index and $PM_{2.5}$ concentrations in North China during the 2015/2016 *El Niño* event. Mean $PM_{2.5}$ concentrations in North China were significantly higher in 2015 (51 µg/m³–95 µg/m³) as compared to 2017 (41 µg/m³–74 µg/m³).

Similar spatial patterns for $PM_{2.5}$ concentrations in the VTAPA were observed throughout the period (2009–2016) in which the majority of PM pollution is concentrated around the centre and towards the south-western region of the VTAPA. These spatial patterns are comparable to those observed by Thomas (2008), who modelled PM_{10} concentrations in the VTAPA using a dispersion model. Due to the low dispersion potential of pollutants in the VTAPA, high $PM_{2.5}$ concentrations were clustered in the central to the south-west region over the cities of Vanderbijlpark and Sasolburg, where heavy industrial (iron and steel, ferroalloy and petrochemical) activities, domestic burning and mine operations take place. Spatial distributions for the VTAPA show that high $PM_{2.5}$ concentrations were also concentrated in the northern part of the area. The main source for $PM_{2.5}$ in this area is residential combustion from the Soweto township and windblown dust from gold mine dumps.

Conclusion

This study evaluated the potential value of satellite remote sensing as a viable alternative to $PM_{2.5}$ ground-based monitoring in the VTAPA. There was a poor agreement between satellite-retrieved $PM_{2.5}$ estimates and ground-level $PM_{2.5}$ measurements. Satellite retrievals tended to overestimate $PM_{2.5}$ concentrations resulting in inflated values throughout most of the VTAPA. According to Kneen et al. (2016), due to financial constraints in South Africa, monitoring stations are placed in regions with the predicted worst air quality that is mainly urban and industrial centres. This will lead to mainly high values being used in the calibration of $PM_{2.5}$ estimates in the GWR model which in turn can result in the overestimation of satellite-retrieved $PM_{2.5}$ concentrations. Therefore, in order to improve the accuracy of the GWR model for satellite retrievals, the positioning of ground-based stations in South Africa needs to be optimised so as to have monitoring data that is more spatially representative.

The relationship between AOD and $PM_{2.5}$ is an important source of uncertainty in satellite retrieval accuracy as the AOD-$PM_{2.5}$ relationship can vary across space and countries. This could have contributed to some of the inconsistencies between ground measured and satellite-derived $PM_{2.5}$ concentrations for the VTAPA. There is a need for an independent assessment of the AOD-$PM_{2.5}$ relationship through an integrated monitoring strategy like SPARTAN (Surface PARTiculate mAtter Network) in which $PM_{2.5}$ monitoring instruments are collocated with ground-based sun photometers for AOD measurements. This will help in evaluating AOD-$PM_{2.5}$ model accuracy and enhance $PM_{2.5}$ estimates from satellite AOD retrievals.

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Author contributions

The majority of the work was conducted by Luckson Muyemeki, who was responsible for data processing, analysis, interpretation, and writing the manuscript. Stuart. J. Piketh and Roelof Burger conceptualised the study and assisted in interpretation of data and editing the manuscript.

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Research article

Changes in health risk associated with air pollution and policy response effectiveness, Richards Bay, South Africa

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Abstract

Research shows that more than 5.5 million people die prematurely every year due to household and outdoor air pollution placing it as the fourth highest-ranking risk factor for mortality globally. In South Africa, air pollution is a key concern in urban areas with high population density, but also in rural areas where electricity is not the main source of energy. Approximately 10% of total mortalities in 2015 were attributed to respiratory diseases. With this, pollution policy intervention, both national and international, has become not only a necessary but a vital tool for the protection of air quality. The National Ambient Air Quality Standards and Minimum Emission Standards were introduced in 2009 and 2012, respectively. To ascertain the effectiveness of these interventions, this study used the case of Richards Bay, a highly industrialised town, to determine changes in health risk associated with air quality pollution exposure. Twenty years' data of air pollution-related mortality causes between 1997 and 2016 were analysed to determine the changes in trends, ranking and the Years of Life Lost as a result of pollution exposure. Results indicate a slight improvement in air quality and related health benefits. There was a 24% decrease in the Years of Life Lost due to air quality-related diseases post 2009. Cases of cerebrovascular diseases, which is the main cause of pollution-related mortality, remains an issue that requires continuous attention. The study concludes that air quality policy and its implementation is working to a reasonable extent. However, the increase in mortality due to certain disease cases such as bronchus and lung cancer could signify that the pollution control efforts need to continue and be enhanced. The increase in acute lower respiratory infections, which adversely affects children, is also of concern.

Keywords

Air pollution health effects, pollution management, air quality policy, Richards Bay, South Africa

Introduction

Lung and bronchus cancer, asthma, acute lower respiratory infections (ALRI), ischemic heart diseases (IHD), cerebrovascular diseases (CEV) and chronic obstructive pulmonary disease (COPD) are disorders that have been widely associated with air pollution and mortalities as a result (Ghanbari Ghozikali et al., 2016; Lelieveldwt al., 2015; WHO, 2016). Research shows that more than 5.5 million people die prematurely every year due to household and outdoor air pollution, placing air pollution as the fourth highest-ranking risk factor for death globally (Brauer et al., 2015; Forouzanfar et al., 2015). It is estimated that approximately 85% of the world's population lives in areas where the World Health Organization (WHO) air quality guidelines are exceeded (Brauer et al., 2015).

In South Africa, where approximately 10% of total mortalities in 2015 is attributed to respiratory diseases (Stats SA, 2016), air pollution is a key concern. This is intensified in urban areas with high population density, extensive industrial set up and traffic; but also, in rural areas where electricity is not the main source of energy (Bradshaw et al., 2003; Langerman et al., 2018; Norman et al., 2007). High ambient sulphur dioxide (SO_2), nitrogen dioxide (NO_2) and fine particulate matter (PM_{10}) concentrations are common in many areas, primarily due to fossil fuel burning (Scorgie, 2012).

The Richards Bay area, which is the focus of this study, is faced with similar air quality pollution challenges (Okello et al., 2018).

Study aim

The study aimed to determine if air pollution policy interventions have been effective in reducing air pollution levels and thereby improving health. This was achieved by analysing changes in health risk (mortalities) associated with air quality pollution exposure in Richards Bay for twenty years between 1997 and 2016. The study analysed significance in trends of mortalities, Years of Life Lost (YLL) and changes in the ranking of mortality causes before and after the introduction of National Ambient Air Quality Standard (NAAQS) and Minimum Emission Standards (MES) for industrial facilities. NAAQS and MES were introduced in 2009 and 2012 respectively. Also analysed were the perceptions and number of air quality-related complaints recorded through the Richards Bay Clean Air Association (RBCAA) complaints handling mechanism.

This study supports South Africa's desire for development that protects public health through health-based air quality standards as envisioned in Chapter 2, Section 24 of The Constitution of the RSA of 1996 which states that:

"Everyone has the right— (a) to an environment that is not harmful to their health or well-being; and (b) to have the environment protected, for the benefit of present and future generations…"

Study area and air quality concerns

Richards Bay, a growing metropolitan, has several industries close to residential areas (Okello & Allan, 2015). The town, located in the local uMhlathuze Municipality, which is part of the wider King Cetshwayo District Municipality (KCDM), is a major industrial hub of the KwaZulu-Natal (KZN) Province of South Africa. It is one of the country's strategic economic zones designated as an 'Area of National Economic Significance' (uMhlathuze Municipality, 2018). It hosts the largest coal export terminal in the world and the second-largest port in South Africa. Additionally, there are several commercial, light and heavy industrial activities such as paper, fertilizer, sugar production and heavy mineral mines. Sugarcane and forestry burning, pesticide usage and dust associated with agricultural processes is common, especially during harvesting time (Jaggernath, 2013). These can be considered to jointly contribute to air quality concerns in the Municipality and surrounding areas (Jaggernath, 2013; Okello et al., 2018). The surrounding urban areas include the town of Empangeni, Felixton, Mtunzini and Enseleni. Figure 1 shows the location of the local uMhlathuze Municipality and the suburbs relative to major industries.

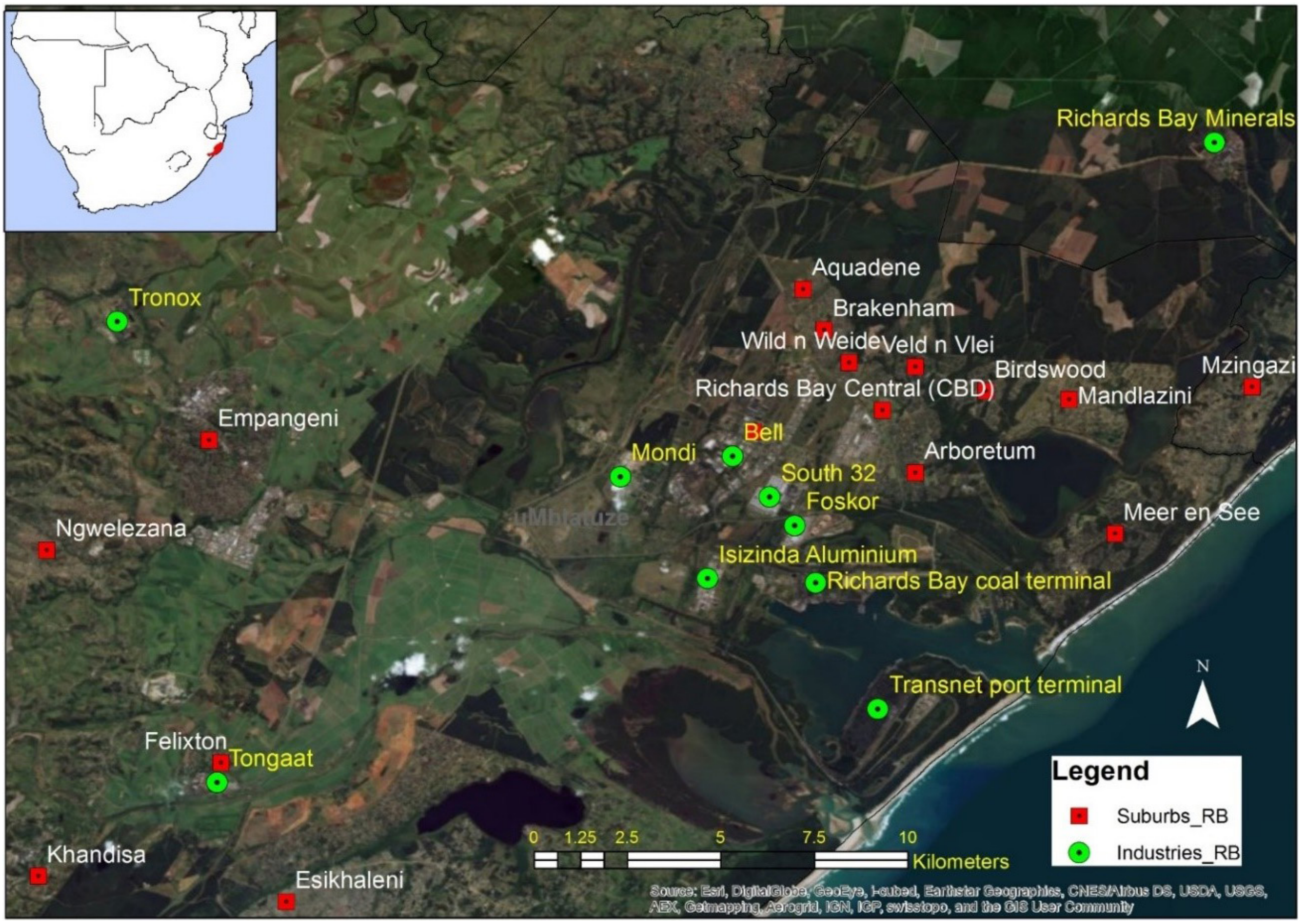

Figure 1: *uMhlathuze Municipality (Richards Bay industries and surroundings area suburbs)*

In terms of exposure, the year 1994 triggered major air pollution concerns in Richards Bay (Savides, 2011). During this time, an emission incident at the fertilizer manufacturing company, Foskor, forced the evacuation of the central business district and resulted in a fatality and multiple cases of hospitalization. This incident resulted in a public petition that subsequently led to the formation of the RBCAA (Okello & Allan, 2015; Savides, 2011). Before this incident, air emissions had been a concern, with minimal research conducted, recorded or published.

Through its network of air quality stations, the RBCAA has documented ambient air quality data collected over 20 years. This has enabled pollution trends and the significance thereof to be established (Okello et al., 2018).

Legislation and policy instruments for air emissions reduction

Several studies have qualified air quality legislation, limits and thresholds as essential to effective air quality management (Amegah & Agyei-Mensah, 2017; Turnock et al., 2016). These, if well implemented and complied with, serve to indicate what levels of exposure to pollution are generally safe for most people of all age groups over their lifetime (Yamineva & Romppanen, 2017). The WHO global emission standards have been used extensively to evaluate ambient and indoor air pollution levels (WHO, 2005).

In South Africa, policy and legal frameworks for protecting air quality exist (DEA, 2009). The Atmospheric Pollution Prevention Act (APPA) was enacted in 1965 and was repealed on April 1, 2010, with the National Environmental Management: Air Quality Act (NEM: AQA) which was partially enacted on September 9, 2005, and fully enacted on April 1, 2010. Additionally, to protect human health and the integrity of the environment, the NAAQS covering priority pollutants including particulate matter, sulphur dioxide, nitrogen dioxide, carbon monoxide, lead, ozone and benzene were formalized on December 24, 2009 (Table 1). Similarly, MES were developed and formally introduced on November 22, 2012, for Listed Activities, i.e., significant industrial facilities. These were amended in 2015, and more recently in 2018 and 2019 for selected activities.

Until now, the influence of NAAQS and MES as air quality control policy instruments in South Africa has not been widely studied. The answer to whether these instruments have been adequate, or whether their implementation is producing the desired effect is important to shape policy. The few studies undertaken have indicated improvement with benefits to human health (Keen & Altieri, 2016). Tshehla and Wright (2019a) concluded that several legislative strategic objectives of the National Air Quality Act are yet to be met. Richards Bay presents an ideal case study for such a study, given the previous air quality pollution trends, industrial makeup, and proximity of residential areas to pollution sources (Okello et al., 2018).

Health effects, and burden associated with air pollution studies

Emissions from industrial activities, different transport modes, the burning of fossil fuels, biomass fires, aerosol use, and radiation comprise some of the main sources of air pollution (WHO, 2016). Such sources of emissions release gases and substances that are toxic for human beings, the most harmful of which include

Table 1: *South African NAAQS Government Notice 1210 (2009)*

Pollutant	Averaging Period	Standards (µg/m^3)	Standards (ppb)	Allowable Frequency of Exceedance	Compliance Date
Sulphur Dioxide (SO_2)	10-min average	500	191	526	Immediate
	1-hour average	350	134	88	Immediate
	24-hour average	125	48	4	Immediate
	Annual average	50	19	0	Immediate
NItrogen Dioxide (NO_2)	1-hour average	200	106	88	Immediate
	Annual average	40	21	0	Immediate
Carbon Monoxide (CO)	1-hour average	30000	26000	88	Immediate
	8-hourly running average	10000	8700	11	Immediate
Ozone (0_3)	8-hourly running average	120	61	11	Immediate
Particulate Matter (PM_{10})	24-hour average	120	-	4	Immediate - 31 Dec 2014
	24-hour average	75	-	4	01-Jan-15
	Annual average	50	-	0	Immediate - 31 Dec 2014
	Annual average	40	-	0	1 January 2015
Lead (Pb)	Annual average	0.5	-	0	Immediate
Benzene (C_6H_6)	Annual average	10	3.2	0	Immediate - 31 Dec 2014
	Annual average	5	1.6	0	01-Jan-15

particulate matter (PM), carbon monoxide (CO), ozone (O_3), NO_2 and SO_2 (Guerreiro, Foltescu, & deLeeuw, 2014; Mohammadi, Azhdarpoor, Shahsavani, & Tabatabaee, 2016). These pollutants have been declared as priority pollutants in South Africa (DEA, 2009).

Health impacts result from either short-term or long-term exposure to air pollution (Haagsma et al, 2014). Short term effects include irritation of the eyes (Goudarzi et al., 2016), the inflammation of the respiratory tract, which causes coughing, mucus secretion, aggravation of asthma and chronic bronchitis. (WHO, 2016). The long term effects, which result from an extended period of exposure, include lung and bronchus cancer, asthma, ALRI, IHD, COPD and CEV (Ghanbari Ghozikali et al., 2016; Lelieveld et al., 2015; WHO, 2016).

Several studies have demonstrated an association between air quality pollution and health and have shown some benefits of legal intervention (Keen & Altieri, 2016; Langerman et al., 2018; Naiker et al., 2012; Norman et al., 2007). A study among the community living in the north-west of the City of Cape Town near petrochemical processing operations showed an association between asthmatic symptoms in school children and a meteorologically estimated petrochemical emissions dose (Norman et al., 2007). Another study estimating the burden of disease in South Africa concluded that outdoor air pollution in urban areas was estimated to cause 3.7% of the national mortality from cardiopulmonary disease and 5.1% of mortality attributable to cancers of the trachea, bronchus and lung in adults aged 30 years and older, and 1.1% of mortality from ALRIs in children under 5 years of age (Norman et al., 2007).

Yet again in South Durban, a health study aimed at assessing the influences of industrial and vehicular emissions on respiratory health found that relatively moderate ambient concentrations of NO_2, NO, PM_{10}, and SO_2 were strongly and significantly associated with reduced lung function among children with persistent asthma (eThekwini Municipality, 2007). The study, which estimated lifetime cancer risks from inhalation of pollutants, indicated that children attending primary school in south Durban, compared to the northern suburbs, had an increased risk of persistent asthma and for marked airway hyperactivity. Higher outdoor concentrations of NO_2, NO, PM_{10}, and SO_2 were strongly and significantly associated with a higher reduction in lung function.

In Richards Bay, a study conducted between 2011-2013, focused mainly on perceptions of air pollution in different suburbs based on economic class. It concluded that the less affluent suburban dwellers felt more affected by air pollution than the affluent dwellers (Jaggernath, 2013). A study for the KwaZulu Natal Department of Agriculture, Environment and Rural Development (KZN-DEARD) found some impacts associated with air pollution but was not conclusive on the link between health and air pollution on the populations due to limited long term data (KZN-DEA, 2014).

Methodology

Data sources

The data on mortality was obtained from Statistics South Africa (Stats SA), the custodians of population data, including causes of mortality in South Africa. This data from Stats SA is based on administrative records from death notification forms accumulated by the Department of Home Affairs (DHA) (Stats SA, 2016). It should be noted that the analyses do not include factors such as cigarette smoking that may predispose people to respiratory complications but rather to air pollution-related mortality in general. Data on the trends of air quality pollution related complaints was obtained from the RBCAA.

Data analyses

The mortality endpoints or causes analysed include lung and bronchus cancer, asthma, ALRI, IHD, CEV and COPD (Lelieveld et al., 2015; WHO, 2016).

The data obtained was aggregated in terms of age groups 0-4, 5-24, 25-64, and 65+ years of age for ease of interpretation, as different mortality endpoints affect different age groups differently. Further, total mortalities before and after the promulgation of NAAQS and MES were analyzed using the Mann Kendall test (MK-tests) (Guerreiro et al., 2014; Koudahe et al., 2017) to determine any significant change. This test is used to analyse data collected over time for consistently upward or downward trends ("monotonic trends"). Being a non-parametric test, the MK trend test works for all distributions, including for data that is not normally distributed. The test is robust in that it can be used to find trends for as few as four samples (Guerreiro et al., 2014).

YLL analysed considered the age at which mortalities occur, giving greater weight to mortalities at a younger age and lower weight to mortalities at an older age. The indicator measures the YLL due to a cause as a proportion of the total YLL lost in the population due to premature mortality (Devleesschauwer et al., 2014)

The number of YLL is calculated by summing the number of mortalities at each age between 1-75 years, multiplied by the number of years of life remaining up to the age of 80 years.

$$\text{YLL} = \sum_{i=1}^{74} a_i d_i \quad (1)$$

Where:
i = age
a_i = no. years of life remaining to age 80 when death occurs between ages i and i+1
d_i = no. of observed mortalities in the population under investigation between aged i and i+1

Assuming a uniform distribution of mortalities within age groups, a_i = 75 - (i+0.5) and therefore:

$$\text{YLL} = \sum_{i=1}^{74} (74.5 - i) d_i \quad (2)$$

The perceptions of residents were obtained through an online survey that was conducted in October 2018 using Evasys online survey system (Okello et al., 2020). Complaints data was obtained from the RBCAA, which has a very robust system of air quality complaints handling (RBCAA, 2018).

Results and Discussion

In this section, the results of trends and significance in mortality, as well as YLL before and after the introduction of the NAAQS and are discussed. Additionally, changes in the ranking of mortality due to pollution-related diseases and the results of the residents' perceptions and complaints are examined.

Trends in mortality due to air quality-related diseases

Absolute trend and significance thereof

Twenty years of data analyzed indicate a steady increase in mortality (almost double) from 1997 to 2003. This data includes the total number of mortalities attributed to asthma, CEV, IHD, lung, trachea and bronchus cancer, ALRI and COPD. After 2003, a general decrease in mortality is observed in the wider KCDM.

The local uMhlathuze Municipality contributes almost half of the mortalities in KCDM (Figure 2). This could be attributed to its larger share of population size, industrial make-up and pollution concentration compared with the wider KCDM. When the Mann-Kendall trend test for significance is applied on mortalities at both the local uMhlathuze Municipality level and the wider KCDM level (2003 onwards), a statistically significant decreasing trend is seen in the number of moralities at the wider KCDM level. However, at the local uMhlathuze Municipality level, there is a decreasing trend in air quality-related mortality, but the decrease is not statistically significant.

The results of the linear regression model taken from 2003 to 2016 show that, on average, mortality is decreasing and is expected to decrease further. This is important and could signify that efforts to manage pollution are working.

Variation of mortalities among different age groups

Figure 3 shows the trend in mortality compared with the trend of air quality data (SO_2 μg/m^3 and PM_{10} μg/m^3) but also presents the variation in diseases per year. CEV among adults is the main underlying cause of mortality, followed by IHD, asthma, and ALRI. The comparison, especially with SO_2, shows a clear similarity in the trend between air pollution and the related mortality. For example, a rise in pollution in 2004 is commensurate with an increase in mortality due to asthma cases in the same year. SO_2 is known to affect the respiratory system and the functions of the lungs and causes irritation of the eyes (Goudarzi et al., 2016). Consequently, the inflammation of the respiratory tract causes coughing, mucus secretion, aggravation of asthma and chronic bronchitis and makes people more vulnerable to infections of the respiratory tract (WHO, 2016). It is also evident that the decrease in PM_{10}, although not statistically significant, coincides with a decrease in mortalities (Okello et al., 2018).

In Figure 4, a higher rate of mortality is seen amongst the middle-aged (25-64) and older generations (65+) with the middle-aged group being the most affected by asthma, ALRI as well as lung and bronchus cancer. These results mirror those of a study conducted in Richards Bay by the KwaZulu-Natal Department of Agriculture, Environment and Rural Development in 2014 in which mostly the middle-aged adults frequented hospitals for air quality-related ailments. The 65+ age group was most affected by CEV and IHD with mortality rates rising among this age group.

The trends in mortalities related to these diseases are also on the rise except for asthma and COPD, which have a slight downward trend. ALRI and asthma-related mortalities are present among all age groups and represent diseases with more impact on children. ALRI is known to affect all age groups, but the younger population is more vulnerable (Murray & Lopez, 2013; Norman et al., 2007).

Changes in health risk before and after the introduction of NAAQS and MES

Data analysed before NAAQS and MES promulgation (2003-2009) and after (2010-2016) indicated a decrease in CEV mortality among the 15 year-old group upwards to 65+ (Figure 5). Mortality

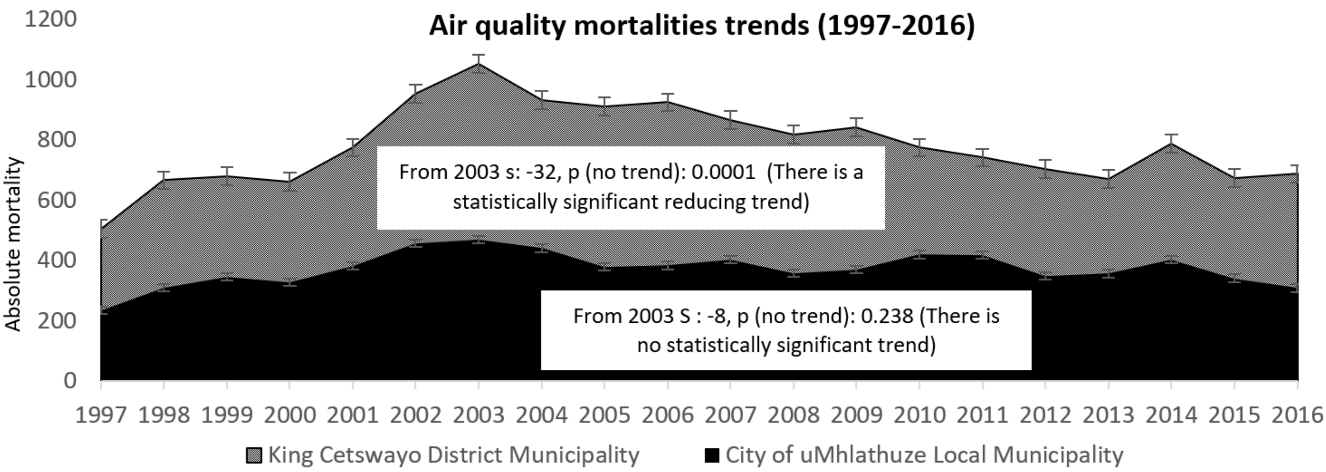

Figure 2: *Air quality-related mortalities in local uMhlathuze Municipality compared to wider King Cetshwayo District Municipality*

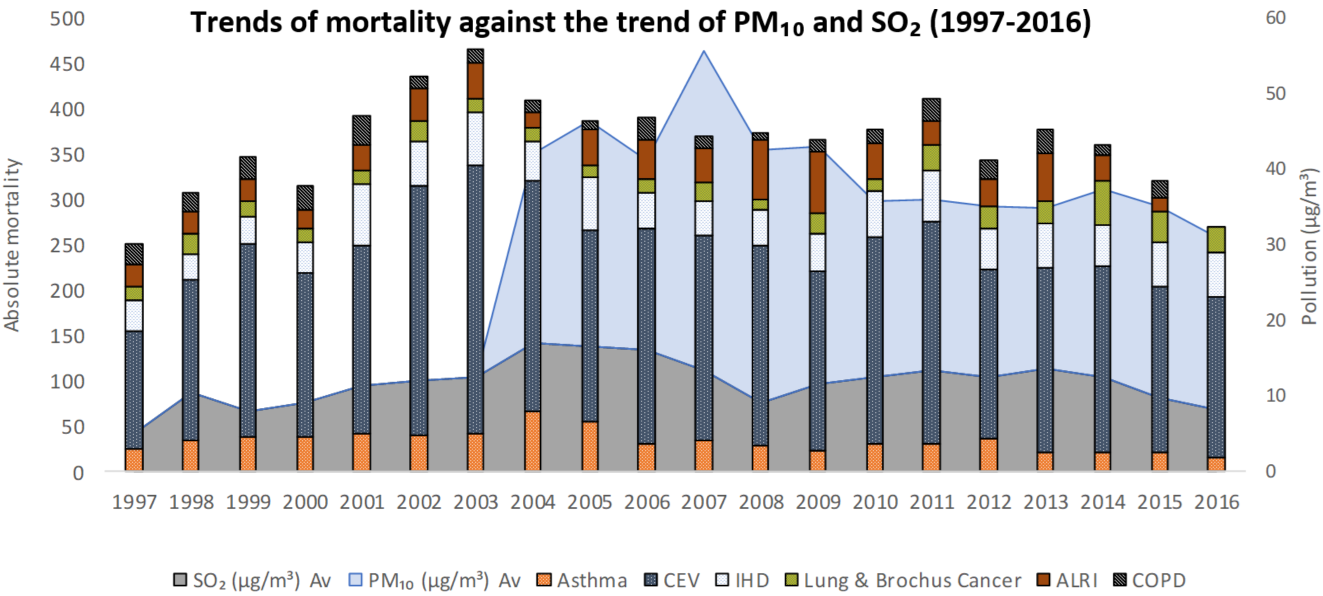

Figure 3: *Trend of air quality-related mortality compared with pollution data (PM_{10} and SO_2 (1997-2016)*

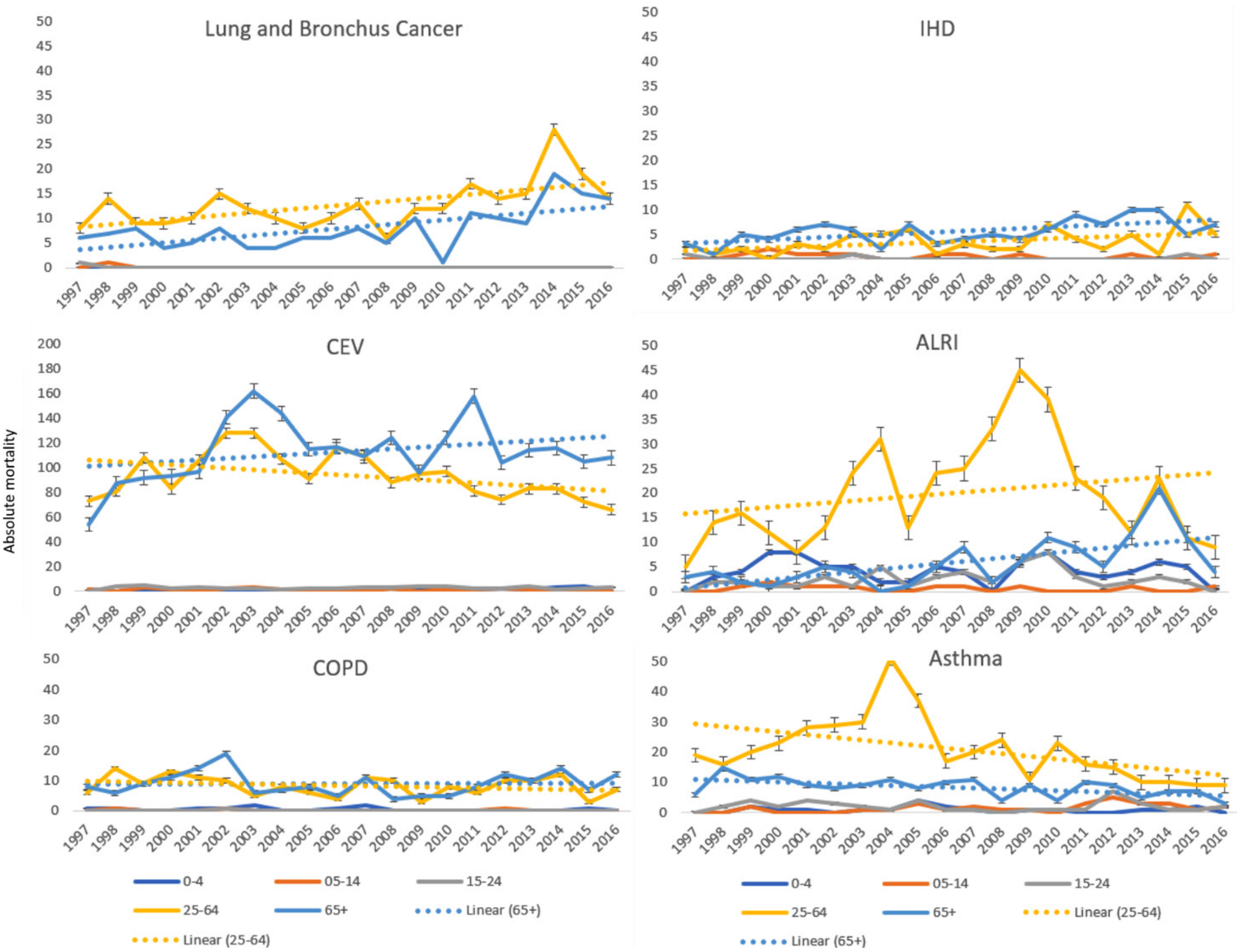

Figure 4: *Trends of air quality-related mortalities in the local uMhlathuze Municipality according to age group and air pollution-related mortality cause*

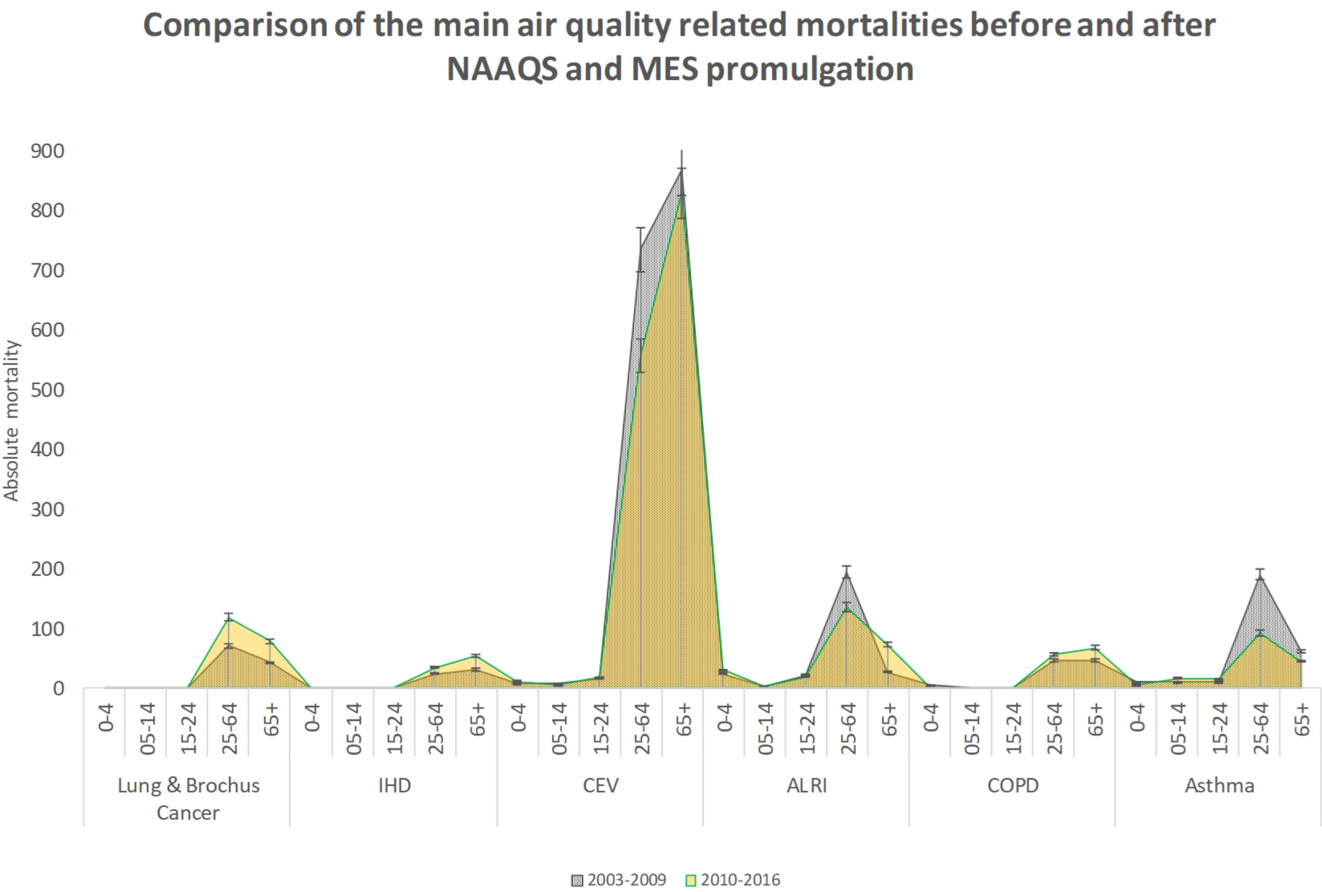

Figure 5: *Mortality causes before and after the implementation of the NAAQS and MES categorized in study age groups*

Table 2: *A comparison of YLL before and after the promulgation of NAAQS and MES*

2003-2009							
All Gender	Population (Census 2011)	Deaths	Deaths per 1,000	Av. Age at death	Standard LE	YLLs	YLL per 1000
0-4	36,456	47	1	2	80	1.423	39
5-14	61,875	22	0	10	72	649	10
15-24	75,922	50	1	20	62	1,409	19
25-64	134,586	1,262	9	45	38	28,761	214
65+	10,368	1,076	104	78	12	10,808	1,402
Total	**319,208**	**2,457**	**8**	**58**	**28**	**43,050**	**135**
2010-2016							
All Gender	Population (Census 2016)	Deaths	Deaths per 1,000	Av. Age at death	Standard LE	YLLs	YLL per 1000
0-4	50,730	48	1	2	80	1.423	29
5-14	91,880	25	0	10	72	738	8
15-24	38,998	54	1	20	62	1,522	39
25-64	172,233	994	6	45	38	22,653	132
65+	13,385	1,148	86	78	12	11,531	862
Total	**367,226**	**2,269**	**6**	**60**	**27**	**37,897**	**103**

due to CEV is an indication of the long-term effects of pollution and represents the highest mortality, particularly in the older age groups. Similarly, ALRI and Asthma cases have reduced in the age group of 25-64 (Figure 5). On the other hand, mortality due to lung and bronchus cancer, ALRI, IHD, as well as COPD, have increased. The decrease in mortality mirrors the decrease in ambient PM_{10} and SO_2 concentrations measured by the RBCAA (Okello et al., 2018).

The cases of increase in mortality can also be considered as a lag, that is, having been affected previously before the introduction of air quality standards and thus manifesting the long-term effects of air pollution before the introduction of the new standards post-2010.

Year of Lost Life Comparison

Another metric used to determine the change in mortality before and after 2010 is the analysis of YLL per 1000 (5 years before and after the promulgation of NAAQS and MES). The results indicate a 24% decrease in the YLL due to air quality-related diseases (Table 2). The decrease can be observed across all age groups except for the 15-24-year-old where there is a slight increase although with few mortality cases. It appears that the adults and the older generation are now living slightly longer.

This result is important in that it indicates an improvement in air quality, but also signals the need for more pollution control.

Changes in the ranking of pollution-related mortality causes

On ranking the six mortality causes considered (with one as the highest cause and six as the least), CEV and IHD remain the top two even after the introduction of the NAAQS and MES. A reduction in asthma can be observed from the third-highest to fifth in the ranking. ALRI and cancer have increased one step up. (Figure 6)

Residents perceptions and complaints

The results of the survey undertaken in Richards Bay and the surrounding community indicate a cautious concern over air quality. Most of the public perceives the air quality as fair or

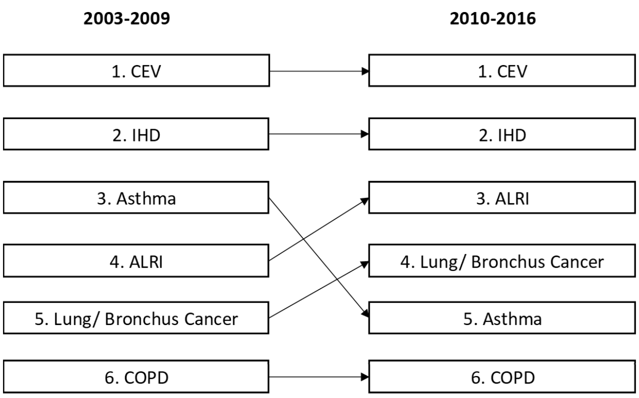

***Figure 6:** Ranking of air quality-related mortalities before and after the introduction of the NAAQS and MES*

poor (Okello et al., 2020). The fair rating is likely to be a result of a downward trend in pollution, particularly PM_{10} and SO_2 (Okello et al., 2018). Nonetheless, widespread sporadic pollution events over the airshed continue to occur. Residential areas closer to main pollution sources such as CBD and Arboretum seem to experience more pollution.

The main cause of pollution affecting the local uMhlathuze Municipality residents is industrial sources followed by agricultural (sugar cane and agrarian burning) and then general waste burning. These results are similar to previous studies and reports in the area (Jaggernath, 2013; uMoya-NILU, 2014) and point out where the focus should be if further pollution reduction is to be achieved.

Aside from the perceptions, the trends in complaints recorded by the RBCAA over the last two decades are important in assessing the historical changes in air emissions. Figure 7 shows a peak of 379 complaints in 2004 and then a drop thereafter. The RBCAA recorded a total of 3,638 complaints between 2000 to 2017, most of which were attributed to industries around the local Municipality's CBD (RBCAA, 2018).

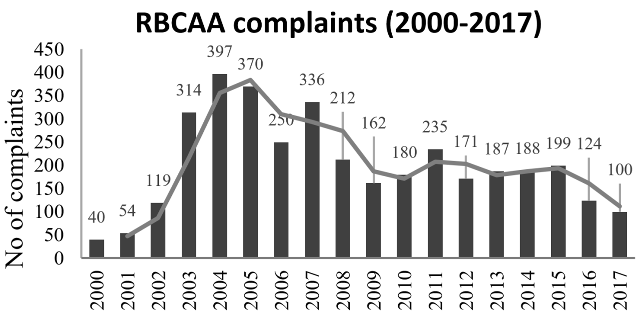

***Figure 7:** RBCAA registered complaints trends showing a peak in 2004 (RBCAA, 2018)*

Conclusion and Recommendations

The study aimed to analyse changes in health risk associated with air quality pollution exposure in Richards Bay before and after the introduction of the NAAQS and MES in 2009 and 2012, respectively.

We conclude that there is a slight improvement in air quality and health benefits that could be attributed to policy implementation. This is based on the results, which indicate a reducing trend of incidents of air quality-related mortalities, although in the local uMhlathuze Municipality it is not statistically significant. There is a 24% difference in YLL before the promulgation of NAAQS and MES and thereafter, a factor that points out to an improved situation. More so, the number of asthma cases has greatly reduced between the period before and after NAAQS and MES. Lastly, there is a perception that air quality is fair and complaints to the RBCAA have reduced markedly since 2004.

One would argue that the reducing mortality trend could be a result of several factors, among others: the introduction of NAAQS in 2009, the implementation of MES for Listed Activities from 2012, the pressure on industrial emission sources from

NGOs such as the RBCAA and/or the implementation of the KCDM air quality management plan from 2014. It could also mean an improvement in health care intervention, or increased migration and emigration, which would impact the observed trends.

Nonetheless, the increase in mortality due to certain disease cases such as cancer of the bronchus and lung, the onset of which could have been prior to 2010, signifies that the pollution control efforts need to continue and be enhanced. The increase of ALRI, which adversely affects children, is of concern. Cases of CEV in the younger, as well as the older generation, is still an issue that requires continuous monitoring and intervention. A recent study in Limpopo, South Africa with similar results, (Tshehla & Wright, 2019b) has suggested a revision of the current South Africa PM_{10} standards to be comparable to the WHO guidelines. This is desirable to improve the protection of human health and well-being.

While the study examined mortality in the last 20 years, further analysis of data in years to come may present more information on policy efficacy. This makes it important to continue with and support monitoring efforts currently on-going. Due to time and resource constraints, this study did not examine morbidity data (hospital admissions, loss of workdays, school days, etc.) which could be used to improve the understanding of policy efficacy. Morbidity data can also be used to understand Disability Adjusted Life Years, which include YLL and Years Lived with Disability. Potential still exists to use modelled air quality predictions to postulate mortalities in the future. Besides, there could be other predisposing factors to respiratory complications such as cigarette smoking that were not singled out.

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The authors wish to thank Statistics SA for data provided on mortality due to air quality-related outcomes. Without this data, analyses of trends and the efficacy of policy implementation would not have been possible. We also thank Tronox KZN Sands and my current employer Base Titanium for study assistance in attending workshops and seminars related to the PhD program. We hope this paper contributes in one way or another on the overall air quality of the local uMhlathuze Municipality, KCDM, South Africa and beyond.

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Research article

Perceptions of external costs of dust fallout from gold mine tailings: West Wits Basin

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Abstract

Mining is essential for the South African economy, just like in many developing African nations. In 2017, mining was reported to contribute 6.8 % to the South African GDP and provided more than 460 000 jobs. Though the sector adds an enormous amount of value to the country, its activities have significant impacts on the environment and the socio-economic factors of society. The environmental impact of mining operations includes air pollution from dust and the well-documented impact on water resources in the form of Acid Mine Drainage (AMD), creation of sinkholes and pollution of agricultural soils. Dust remains a persistent problem in South African urban areas due to the climatic conditions, extensive surface quarrying, unrehabilitated tailings storage facilities and mineral processing. However, very little is reported on the social and economic costs that accrue due to poor ecological management. Some scholars assert that despite the Mine Health and Safety Act, deposition monitoring guidelines and national dust regulations, South Africa still experiences persistent dust problems, especially in coal and gold mining districts. This paper investigates the perceptions of society on the effect of gold production dust pollution in and around a gold mining village (hereinafter referred to as the “gold mining village”) in South Africa. A mixed method was used, where a questionnaire and interviews were conducted to examine the gold mining village perceptions on dust pollution and their socio-economic environment. This paper further examines perceptions on how poor and premature mine closure through liquidation results in unrehabilitated mine tailings and how this has significant impacts on the quality of life of individuals and surrounding businesses. The community being investigated in this study perceives the dust fallout impact to be a threat on their living conditions. The paper finds that the community believes it incurs medical and financial expenses due to treating respiratory-related diseases triggered by dust fallout.

Keywords

Mine liquidation, mine closure, environment, dust, socio-economic costs, perceptions

Introduction

Recently the profitability of gold mining operations in South Africa has been reduced through increases in labour and operational costs, and stagnant productivity (Minerals Council of South Africa 2018). This has resulted in some gold mining shafts being closed or placed under care and maintenance. South Africa is known to have a significant legacy of inadequately rehabilitated and closed mine sites, attracting an estimated 70 000 illegal miners (Digby 2016).

The processes of liquidation and business rescue have allowed mining companies to evade costly closure obligations (Humby 2014). Liquidation involves an insolvent company, placed under the custodianship of a liquidator, who manages the fair and equitable allocation of the company’s assets to its various creditors while the remaining assets go to partners or shareholders. This has led to premature or sudden mine closure, and poor rehabilitation of tailings storage facilities (TSFs), which is believed to affect surrounding communities. Mines that are disused or abandoned by their owners and have not undergone appropriate decommissioning and rehabilitation have a large number of negative impacts on the surrounding community. The adverse impacts include: job losses from the mining activity, security issues relating to illegal mining activities in disused shafts, and ongoing pollution of soil, water and air (Digby 2016).

There are various drivers of premature closure which lead to a degraded environment and affected communities. These drivers include:

- liability shifting amongst companies,
- unclear regulatory leadership on care and maintenance,
- challenges with the enforcement of the integrated closure plan, and generic company regulation relating to transactions,
- poor mine planning, lack of business rescue programmes, as well as an ineffective liquidation process.

Environmental and human rights activists view care and maintenance as a 'faux legal term', referring to indefinitely warehousing mines instead of spending money on rehabilitation (FSE 2018).

Laurence (2006) notes that only a small percentage of mines are closed according to the mine closure plan, with the majority closing prematurely for various reasons. Milaras and McKay (2014) contend that numerous mines do not have contingencies or make specific plans for sudden or emergency closure. Milaras and McKay (2014) argue that there is a lack of institutional capacity in mine closure decision-making, compliance monitoring and enforcement as well as the support of long-term studies on mine closure impacts, costs and remediation.

Thus, the focus of this paper is to investigate the community perceptions on the socio-economic costs of dust fallout in a gold mining village situated in the West Witwatersrand Basin.

The perceptions of the community are assessed to articulate how sudden mine closure can be linked to dust fallout and the effects on society's well-being.

The mining situation in South Africa

Mine liquidation

Liquidation is regulated under many Acts in South Africa. The purpose of liquidation is to dissolve the company in an orderly manner and not to rescue it. The company's existence ceases through the formal process of dissolution (Humby 2014). Post final liquidation a brand-new company can sometimes be constructed.

An early example of a mining company that experienced liquidation, was the Aurora Empowerment System (AES) which took over Pamodzi Gold Ltd in April 2009. The process of taking over was finalised in October 2009. Since 2008, this company had been operating a mine in Orkney, one of the most productive gold mining areas in South Africa (Stuit 2009; Van der Walt, 2009). However, some issues that arouse included that post-liquidation, employees did not receive their salaries.

Sudden mine closure is common in South Africa with catastrophic repercussions for the environment and surrounding communities. The gold mining company, for example, had no closure certificate and was liquidated in 2013. The liquidator and activists failed to gain access to the gold mining company's financial provision. According to Olalde (2017), the Promotion of Access to Information Act (PAIA) documents show the fund sits at about R35 million, a level admitted by the gold mining company to be vastly inadequate to clean up the mine.

Another example of a liquidated mining company is Mintails Mining South Africa; which holds three mining rights, which cover an area of 1751 hectares near Krugersdorp. It is stated that Mintails requires approximately R259 million to complete rehabilitation on those rights, a figure that is far too low, according to the environmental management programme report (FSE 2018). The PAIA documents reveal that the company and related entities hold less than R17 million in funds for rehabilitation (FSE 2018).

During the process of liquidation of a mining company, the financial provision for rehabilitation seems not to be recognised as a special claim against the company's assets to be set aside before satisfying creditors. This forms part of the reason why some mining-affected communities like the gold mining village are faced with environmental impacts from unrehabilitated tailings storage facilities.

Mine closure in South Africa

Mine closure planning is part of the mine life cycle, which includes exploration, pre-feasibility, development through operations to closure and rehabilitation. The closure planning is multi-dimensional and is mutually dependent on the surrounding communities (ICMM 2010). In South Africa, mine closure is regulated under the Minerals and Petroleum Resources Development Act (MPDRA) and National Environmental Management Act (NEMA) under the Department of Mineral Resources (now called the Department of Mineral Resources and Energy, DMRE) and the Department of Environment, Forestry and Fisheries, (DEFF) regulatory authorities.

The best practice of mine closure planning is to consider closure at the exploration phase, when the feasibility of the mine, design and mining permits are established (Stacey et al. 2010). Mines typically close at the end of their life cycle, when the mineral resources and reserves are depleted. However, recently a number of mines are closing prematurely for reasons including diminishing economic feasibility resulting from changes to the mineral resource, geological complexities that were not anticipated in the planning stages and a changing political, legislative and labour regulatory environment (Laurence 2006).

Fourie and Brent (2008) point out that South Africa has adequate policies and legislature on mine closure, especially when considering social and community development. The promulgation of the MPRDA aims to ensure that mining companies take responsibility for community growth and development. The MPRDA Section 43 (3) states that a holder of a mining right must apply for a closure certificate upon cessation of mining operations or relinquishment of any portion of land to which the right relates.

Until mid-2014, mine closure planning was regulated by the MPRDA. Since then, it has been regulated under the National Environmental Management Act (NEMA) as a sustainable development construct. Although mine closure is regulated under NEMA the enforcing department is not DEFF but DMRE. Some of the elements of mine closure, such as relinquishment are still regulated by the MPRDA. Section 2 of NEMA provides specific guidance on the closure of mining operations, mandating that a mining right holder must:

1. Rehabilitate the environment as far as reasonably practicable to its natural state or to a land-use which conforms with the generally accepted principle of sustainable development;
2. Set aside a financial provision, which only the state can access, to ensure such rehabilitation occurs; and
3. Retain liability for environmental damage even after closure of the operation.

Most attention has focused on the financial provision, the duration of liability and the gaps which allow companies to contract out of their mine closure obligation (WWF 2012; Humby 2013). The issue with this provision is that it only applies if the new order mining right has been issued for a particular mining company. In the case of the gold mining company, this new order mining right had not been issued prior to the liquidation, thus neither the DMRE nor the liquidator could step in to take care of the community and avoid environmental degradation.

Air pollution by dust challenges

The pollution of air, soil and water caused by mining activities has detrimental impacts on the health and well-being of surrounding mining communities. The South African Human Rights Commission (2016) study on mining-affected communities in the Gauteng Province reports that most mining-affected communities complain about increased levels of dust, deteriorating health and threatened food security. Communities have drawn attention to poor environmental remediation and overall management (SAHRC 2016). Statistics show that South Africa produced an estimated 468 million tonnes of mineral waste per annum between 1997 and 2001 (DWAF 2001). Of this quantity, gold mining waste accounts for 221 million tonnes – equivalent to 47% of all mineral waste in South Africa.

NEMA acknowledges that the state's environmental obligation is linked to the responsibility to respect, protect and fulfil socio-economic rights. Environmental degradation due to a failure to rehabilitate tailings storage facilities by mining companies infringes human and socio-economic rights. Environmental rights go hand-in-hand with rights to sufficient food, water, health, land and dignity. Anglo Gold Ashanti (2004) reports that more than 270 tailings dams exist in the Witwatersrand Basin, which covers 400 km^2 of land.

Air pollution due to unrehabilitated tailings dumps is known to trigger respiratory diseases in surrounding communities. Nkosi, Wichmann and Voyi (2015) found that people residing near mine dumps are exposed to dust from these dumps, which pose an

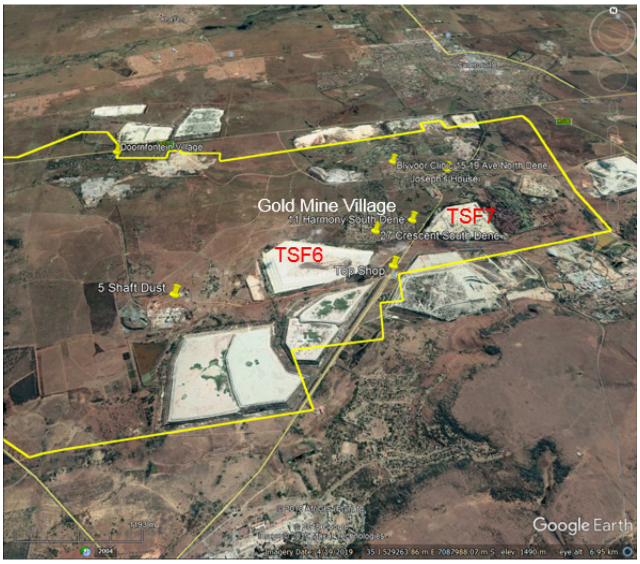

Figure 1: *Tailings storage facility number 6 in relation to the community location.*

increased risk for respiratory disease. Illnesses such as asthma, chronic bronchitis, chronic cough, emphysema, pneumonia and wheeze are associated with communities residing near mine dumps at a distance of less than 5 km (Benchmarks Foundation 2017). The respiratory illness is triggered by the fact that tailings material is usually fine-grained and can be inhaled; the material also contains toxic heavy metals.

Air quality monitoring and management are regulated under the National Environmental Management: Air Quality Act, 39 of 2004 (NEMAQA). In 2013 DEFF released the National Dust Control Regulations, founded on the need to prevent pollution and ecological degradation and ensure the protection of the right to an environment that is not harmful to health and well-being. Moreover, Section 33 of NEMAQA requires mining companies to notify the minister in writing if mining operations are likely to cease within five years. Despite all these regulations and standards in place, non-compliance is still prevalent in the mining industry.

In Soweto, for example, the communities residing near tailings dumps have ongoing respiratory illnesses (BMF 2017). Harvard Law School International Human Rights Clinic (HLSIHRC) points to the chemical toxicity of the Witwatersrand tailings dumps (HLSIHRC 2016). These tailings dumps contain significant levels of arsenic, cadmium, cobalt, uranium, lead and zinc (Coetzee et al. 2006; Heyl 2007 in van Eeden et al. 2009). Uranium is of the most significant concern because it is radioactive. When inhaled or ingested, can cause brain damage and lung cancer in the long term (Van Eeden, Liefferink and Durand 2009). Other scientific research has shown that when water containing uranium is rubbed against animal skin, it causes skin irritation and damage.

Study area

The gold mining village is found in the West Witwatersrand Basin, located 6 km south of Carletonville, in the Gauteng Province of South Africa (Golder Associates 2016). The gold mining village is situated within the jurisdiction of the Merafong City Local Municipality. The gold mining company first commenced in the 1930s and continued up until August 2013, when it was placed under liquidation. The mine is believed to have been liquidated 14 years ahead of schedule due to a slumping market and internal labour disputes. The mine generated about £2.5 million of gold, silver, uranium and other minerals, but it is now a volatile wasteland (DRDGOLD 2007). Before the sudden closure of the mine, there were ten tailings (slimes) dams on the mine property, of which only two were active. Of the two active slimes dams on the property the Number 6 Slimes Dam (TSF6) was the main waste disposal area while Number 1 Slimes Dam was reserved for use under emergency conditions. Figure 1 shows TSF 6 located near (60 m) from the community of the gold mine village.

Challenges

In 2016, when the residents of the gold mine village were interviewed by Lawyers for Human Rights, they mentioned that the air was not clean (Lawyers for Human Rights 2017). Residents said that tailings caused health problems including amongst others cancer, asthma, skin rashes, eye irritation and eczema. However, a lack of local epidemiological studies has made it nearly impossible for communities near mine dumps to pursue litigation against mining companies. Residents also mentioned that there were several deaths in the area due to illnesses such as tuberculosis (TB), which they believe, are exacerbated by the dust (Lawyers for Human Rights 2017). The community complaints about the fallout dust problem were mostly during the windy season, from July to October 2014. There was non-compliance with the residential area limit in the months mentioned previously. In September and October of 2014, there was non-compliance with the non-residential area limit, which is concerning for environmental pollution. Since two consecutive months were non-compliant, there was overall non- compliance in 2014 in the area. Unfortunately, no mitigation measures were undertaken since the gold mining company was liquidated.

Methodological approach

This research utilises a mixed method approach to investigate the socio-economic costs of dust at the gold mine village. Semi-structured questionnaires and interviews were designed and conducted with the following groups; residents of the mine village, businesses in the mine village and personnel from the Centre of Environmental Rights, Lawyers for Human Rights and various liquidators.

In order to understand the socio-economic status of the gold mining village, a household survey was conducted. This data was augmented by census data, Integrated Development Plans, Service Delivery and Budget Implementation Plans. The Department of Mineral Resources and Energy (DMRE) could not contribute to this paper, which is unfortunate since their views and comments would have added significant value to the overall research as they are part of the key stakeholders in regulating mineral resources. It was expected that the DMRE could explain whether they have any plans in place to curb the environmental and socio-economic impacts by holding liquidated mining companies liable during the mine liquidation period.

Sampling

The key stakeholders were identified as informants of this research regarding the socio-economic costs of dust in the gold mine village. A simple random sampling technique was used when administering the questionnaires.

A total of 300 households were visited by five enumerators. The households were first selected at Ward 5, close to the community clinic. The second set of questionnaires were conducted in New Village, located 200 m away from the small local supermarket and about 60 m away from Tailings Storage Facility 6 (TSF6).

Data collection and instrument

The first questionnaire that was designed for surveying the residents of the gold mine village was adapted from the World Health Organisation (WHO) House Health Survey questionnaire to elicit specific, quantifiable information about household demographics, common illnesses linked to dust and health services (WHO 2002).

The second questionnaire (open-ended interview questions) was directed at the businesses of the gold mine village and other stakeholders, which included Lawyers for Human Rights, liquidators and the Centre for Environmental Rights.

Data analysis

The responses were analysed through the Statistical Package for Social Sciences (SPSS) Descriptive statistical analysis supported in understanding the community perceptions regarding dust, socio-economic impacts and the premature mine closure.

The interview responses were interrogated through conceptual analysis, the number of concepts to code, distinguishing the concepts, coding the text and analysing the results.

Data reliability

The questionnaire directed at residents was first administered to 20 households from Ward 5 and another 20 households in New Village. The responses were analysed, and some questions were amended, with ambiguous questions being rephrased or removed. The questionnaire was re-administered again to the same 40 individuals; the same responses were observed, thereby giving us confidence in the robustness of the questionnaires and the stability of the responses. Validity was tested by comparing the two wards, and how the households responded was found to be similar.

Ethical considerations

The study methods and research instrument (questionnaire) was scrutinised and approved by UJ's Faculty of Engineering and Built Environments' ethics committee. The questions were designed such that a respondent could be objective when answering. Confidentiality of the respondents was assured through the anonymity of individuals. It was also explained that respondents have an option to withdraw from the study at any time. The respondents were told how the information would be used, and why it was collected. The respondents were also assured of their safety and security.

Results and discussion

The socio-economic characteristics of the households

The gold mine village is a typical mining town which consists of a mixture of individuals from different language backgrounds, including Afrikaans, Xhosa, Sotho, Tswana and Zulu speaking people. The village consists of about 6000 residents, and approximately 700 households (LHR 2017). A significant number (72 %) of the residents have lived in this town for more than 10 years and originally came to the gold mine village for work purposes. Approximately 52% of individuals in the 25-64 age group in the mining village are unemployed. The youth age 30-39 was mostly found in the village (Figure 2).

There was almost an even split in the gender of the respondents with females being slightly more prevalent at 54%. Some women explained that their husbands had returned back to their homes after the mine was liquidated, and for others, their spouses have part-time employment.

In each house, there were about 4 to 7 individuals residing. This is attributed to the fact that a household is made up of family members and tenants renting rooms inside the house as well as outside cottages. Homeowners are taking on tenants as a means of supplementing income through rentals. It is anticipated that households are larger in size in mining villages like this one due to the surrounding mining activities which promise employment and thus increase migration.

Figure 3 indicates that since the liquidation of the gold mining company in 2013, most residents are unemployed (51 %). This number is higher than the national unemployment rate of 26.7% in 2017 (StatsSA 2018). The residents of the gold mine village explained that they struggled to find employment anywhere around the Carletonville area. Most respondents indicated that the only skills and work experience they had been in gold mining. In a study conducted by the Lawyers for Human Rights in this same mine village, 62% of the people employed by the mine had worked in the gold mine for 10 years and 38% worked for 20 years (Lawyers for Human Rights 2017). When this study was undertaken, the individuals who had some form of employment were involved in economic activities such as mining, agriculture, livestock farming, piece jobs and subsistence business activities.

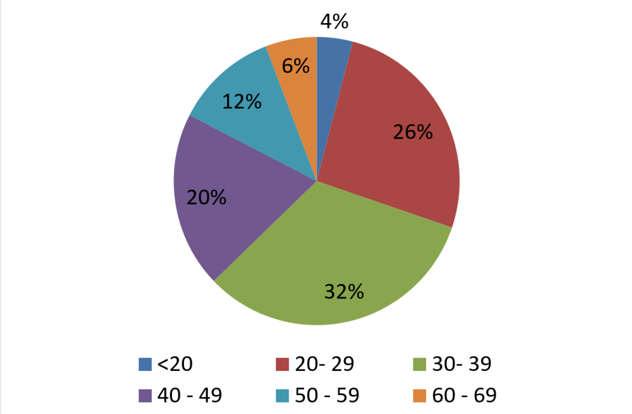

Figure 2: *Age distribution of the respondents*

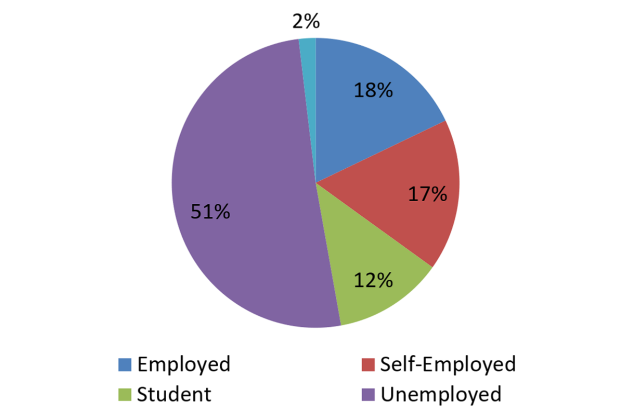

Figure 3: *Employment status of the respondents*

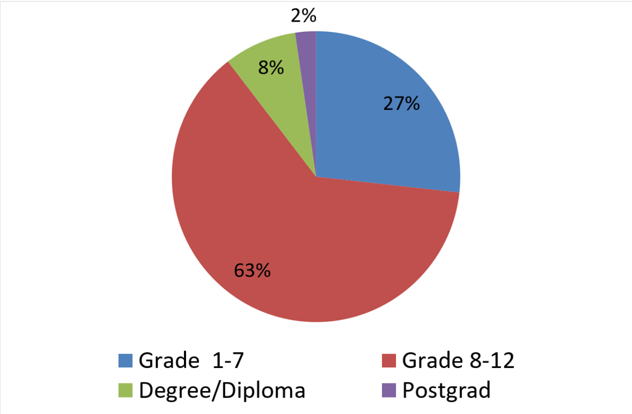

Figure 4: *Level of education of the respondents*

63 % of the residents had completed matric, whereas 27% had not completed their schooling (Figure 4). The national South African household survey reported higher education level as a protective factor for respiratory diseases (Ehrlich White, Norman, Laubscher, Steyn and Lombard, 2004). According to the Census (2011), only 28.4% of South Africans over the age of 20 had completed the twelfth grade, 33.8% had reached high school, and 12.1% had a tertiary qualification, which is reflected in this community.

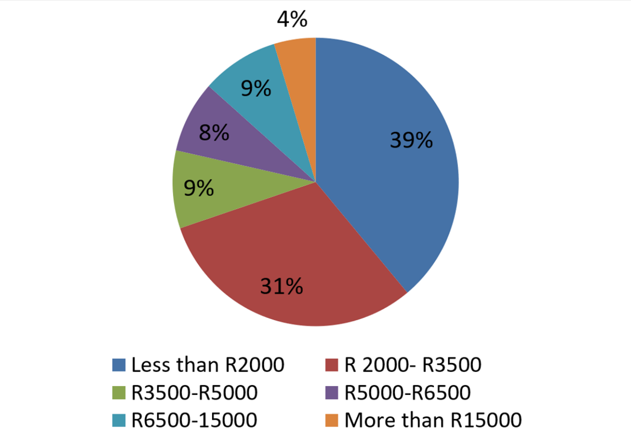

Figure 5: *Monthly income of the respondents*

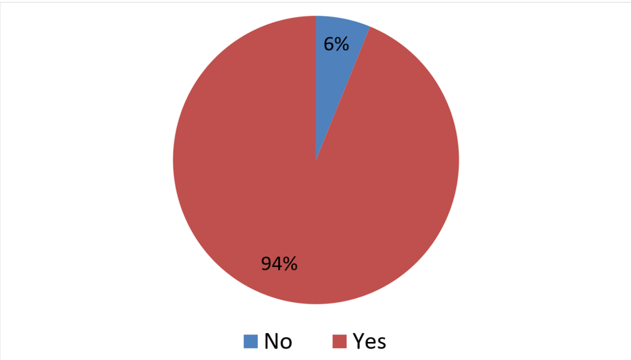

Figure 6: *Fallout dust a problem*

The average monthly income for residents ranged from less than R2 000 (39%) to R3 000 (31%) (Figure 5). This amount is below the minimum wage of South Africa (National Minimum Wage Act 2019). In Gauteng the monthly average income is reported as approximately R13 000 (Census 2011).

Significant factors for chronic respiratory symptoms and diseases are due to residing close to mine dumps, smoking habits, and the use of paraffin for cooking and heating as well as low levels of education (Nkosi et al. 2015). Furthermore, low levels of literacy are associated with low socio-economic status and have been identified as a risk factor for respiratory illnesses and symptoms (Karnevisto et al. 2011). What is observed in the present study accords with the findings of Karnevisto et al. (2011) as the community complained of respiratory illnesses and seemed not to have reached a higher education level.

Only 4% of the respondents indicated that they earned more than R15 000 per month. These individuals are possibly the residents who indicated they have permanent employment. Before the sudden mine closure, 70% of the respondents in this Gold Mining Village reported earning over R4 000 per month. This is of great concern, as some respondents stated that they rely on government social grants for income. Furthermore, some of the respondents mentioned not being able to pay school fees for their children due to a lack of income and unemployment. Table 1 summarises the socio-economic characteristics of the Gold Mine Village community.

Table 1: *Characteristics of the Gold Mining Village households*

Variable	Descriptive Statistics
Age	12% is below 20, 26%: is between 20-29, 32% 30-39, 20%: 40-49 4% 50-59, 6% 60-69
Gender	Female 54%, Males 46%
Employment	Unemployment 51%, Contract work 18%, Self-employed 17%, Formally employed 2%, Students 12%
Education	Below matric 27%, Matric 63%, Degrees 10%
Income	70% earns between R2000-R3000, 4% earns >R15 000
Smoking	78% non-smokers, 14% smokers, 8% ex-smokers
Years lived in the Gold Mining Village	20% (< five years) 41% (5-9 years), 31% (10-20 years) and 8% lifelong resident

The occurrence of smoking in the community was also assessed. Of the respondents, 78% said that they did not smoke, 14% responded in the affirmative while 8% said they were ex-smokers see Table 1. This question was investigated to show that the respiratory illnesses that occurred in this mining village were not necessarily as a result of smoking but could be related to dust fallout. The ex-smokers mentioned that doctors advised them to stop as they had been diagnosed with chronic respiratory symptoms.

Dust challenges in the gold mine village

The residents of the gold mine village were asked whether they considered that dust is a problem to the community. The majority (94%) of the residents responded in the affirmative.

The overwhelming majority of respondents consider dust to be a significant problem. 27% of the respondents stated that dust pollution was a critical problem. 32% stated that they considered pollution by dust to be a very serious problem and 36 % stated that it was a serious problem. Only 5 % believed that dust was not an important problem, with 4% saying it was less serious and 1% saying it was not a problem at all (Figure 7).

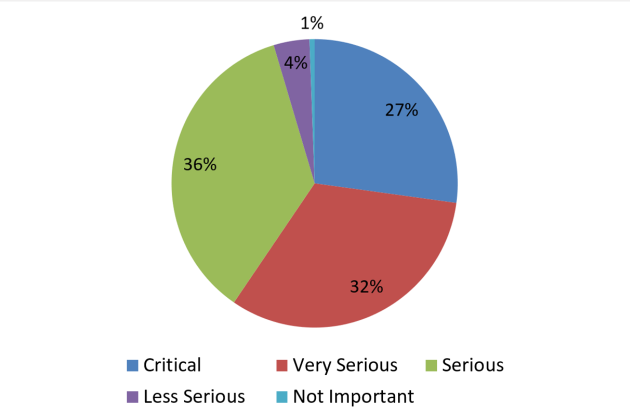

Figure 7: *Level of importance placed on air pollution by dust*

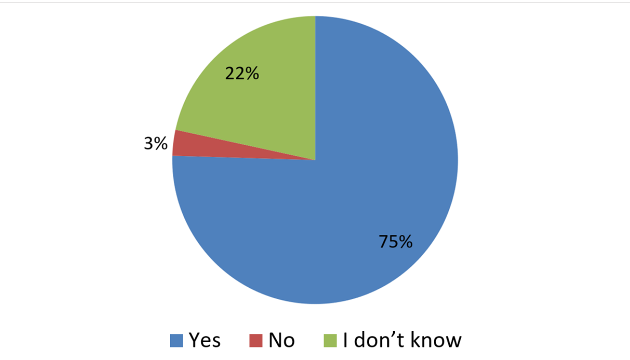

Figure 8: *Dust effects on economic status*

It is evident that the residents of this mine village consider fallout dust to be a significant problem such that they obtained legal assistance from the Lawyers for Human Rights to hold the gold mining company directors accountable for the pollution.

The majority of respondents (63%) answered that they were interested in environmental well-being. Most of the residents (94%) admitted that there is a problem of dust pollution, and specifically emanating from TSF6. The Sotho and Tswana speaking respondents euphemistically called TSF6 'motoro' which means mud. The Xhosa and Zulu speaking people called it 'iindunduma' which means hills. All respondents (100%) agreed that TSF6 was the source of dust causing air pollution.

This poses health threats to the surrounding community, which believes it inhales the toxic dust from the tailings. A similar observation was made by Kitula (2006) in Tanzania's Geita District. There, the Geita Gold Mine Company (GGMC) was closed and the community suffered respiratory illnesses due to dust from poorly rehabilitated tailings dumps. Nkosi et al. (2015) suggest that there is a link between the respiratory problems among the elderly living in or near mining communities in Gauteng and mine waste facilities. They note that exposed communities have a higher prevalence of chronic respiratory symptoms and diseases such as asthma, chronic bronchitis, chronic cough, emphysema, pneumonia and wheeze, compared to unexposed communities.

Similarly, to other residents in mining communities of the West Rand, the gold mine village residents are not amiss in associating their respiratory problems with dust from the surrounding mine dumps and mining operations (Wright et al. 2014). From the responses, 97% of the residents answered in the affirmative when asked whether they think dust fallout triggers any respiratory-related diseases. When the respondents were asked which respiratory diseases do, they suffer from during the windy season, 83% of the respondents stated severe cough, 9% of the respondents said sinusitis, 6% of the respondents said TB and 2% of the respondents mentioned asthma. This affirms findings by the Benchmarks Foundation (2017) in their Soweto household survey, that residents near tailings storage facilities suffered respiratory-related illnesses such as cough, asthma, sinus and TB. This study could not validate the above as a toxicological and epidemiological study would need to be undertaken to prove such claims.

It was also asked whether there were any indoor sources of air pollution (i.e. heating and cooking methods). This was investigated due to the knowledge that people spend more time indoors than outdoors, and indoor pollutant levels are worse than outdoor pollutant levels (Ao et al. 2003). Furthermore, according to a comparative risk study of WHO, 28% of all deaths are caused by indoor air pollution in developing countries (Massey et al. 2009). It was noted that electrical heaters and stoves were used for indoor power generation; as electricity is subsidised by the Merafong Municipality, during the period of mine liquidation. This, therefore, reduced the potential of indoor pollution being a significant threat to the households.

The respondents mentioned that dust was most prevalent in winter (51 %) and early spring (31 %). This concurs with the study by Sithole et al. (2000) which found that nuisance dust fallout is most evident during the windy, dry early spring season, which is late July to early November. The respondents were asked whether they were aware of national dust standards. 90% of the respondents answered in the negative, indicating they were not aware. A follow-up question was posed to find out what individuals wanted to be improved in the standards. The respondents explained that there was nothing wrong with the standards themselves; they did mention, however, that the enforcement of compliance was a problem. The respondents also expressed the hope that the government would strengthen the enforcement, management, monitoring and compliance with standards.

The perceived socio-economic costs of dust

The respondents were asked whether dust affected their economic status in any way (Figure 8); 75% responded in the affirmative.

Other respondents went on to explain that this was something they had never actually thought about, therefore they did not know (22%). According to Article 12 of the International Covenant on Civil and Political Rights (1998), there is a direct link between a healthy environment and quality of life, including the fulfilment of human rights. Similarly, the Committee on Economic Social and Cultural Rights (2002) recognises that the enjoyment of economic, social and cultural rights depends on a healthy environment. From the responses gathered, the community feels that these rights are infringed upon due to the poor air quality.

When asked if dust affect their socio-economic status, the respondents who answered in the affirmative, mentioned medical (97%) and cleaning costs (3%) as the significant external costs of dust. The respondents mentioned that they purchase cleaning detergents and they clean the house more than once. This affirms findings by the Benchmarks Foundation, where the residents of Riverlea found it necessary to clean their homes two to three times per day during the high dust periods (Benchmarks Foundation 2017).

The residents maintained that they perceive the dust to have brought about respiratory illnesses. During the high dust periods, the community mentions that they spend copious money on medicine for coughing, nasal sprays or go to the clinic (R25, four times per month) or doctors (R350-R500, three to four times per month). This confirms work in other areas, that estimate health costs to contribute 75% of the total externalities associated with air pollution (Cropper and Oates 2002; Matus et al. 2011).

The loss of human health creates external costs which invariably lead to overall loss to social welfare. The health effects from air pollution incurs direct and indirect costs to society. Freeman (2003) divides the health effects associated cost into four categories: medical cost, labour cost, averting cost and welfare loss (discomfort, suffering). This study clearly reveals that the community perceives dust impacts to be medical and welfare costs.

Approximately 96% of the respondents perceive dust management to have not improved in the area due to the lack of rehabilitation on TSF6.

The respondents (92%) also mentioned that they get discouraged from going to the shops during windy days because of impaired visibility on the road. This corresponds with what business owners are saying that during windy days when there is dust, there are fewer customers than when there is no dust. Other respondents (8%) mentioned that they go to the shops regardless of the dust. 100% of the respondents go inside the house, close all doors, and windows, and this costs them nothing to prevent nuisance dust from entering the house. However, dust still enters the houses through the ambient air, thereby remaining a case for concern. Other members of the households mentioned that they put wet towels around the windows and they try to sweep the dust out.

The respondents do not realise the indirect cost associated with dusty days. For example, when people go inside the house, close doors, and windows, start opening the heater or utilising water that they would have otherwise not used if there was no dust. Kyung-Min Nam et al. (2010) and Mayeres and Van Regemorter (2008) reveal in their studies that labour and leisure loss are significant economic impacts of air pollution and can affect market equilibrium.

About 71% of the respondents mentioned that they had vegetable gardens. Only 30% of the respondents with gardens said they did not eat the produce from their gardens due dust and bought vegetables from shops. About 88% of the respondents explained that they produced fewer vegetables during the windy season and more during the non-windy season. The concern is that plants absorb radioactive substances from the soil, deposited by dust and are then consumed as food. The continuous consumption of vegetables that are exposed to dust on a daily basis means that there is constant accumulation of radioactive substances in the bodies of the consumers. This becomes a threat to their health in the long run. Therefore, the 70% respondents that agreed to eating vegetables from their gardens are at risk of ingesting toxic vegetables.

Businesses in the small shopping centre located approximately 60m opposite TSF6 listed the following as costs due to dust from the tailings dump:

- Damage to electronic equipment (printer, photocopier and scanner);
- Purchasing dust masks for employees (petrol attendants);
- Absenteeism of employees due to illness; and
- Cooked food products accumulating dust from the tailings dump having to be thrown away.

The economic valuation of health effects can be evaluated based on two approaches: willingness to pay (WTP) or willingness to accept (WTA) and the cost of illness approach (COI). COI is the sum of lost productivity and medical expenses (Quah and Boon 2003). The WTP method measures what individuals would be willing to pay in exchange for improved health. This method was considered in this study.

The community of the gold mine village was asked whether they would be willing to pay to offset the dust fallout impact. Some residents (55%) of mine village indicated that they were not willing to pay to rehabilitate TSF6. However, the remainder mentioned that they were willing to pay, but had no employment and would therefore not be able to contribute to a rehabilitation fund see Figure 9. Income is observed to be a significant factor which influences WTP and education, on the other hand, is known to have a negative influence on WTP.

As can be seen in Figure 10, the bulk of the respondents (56 %) were not willing to pay any money for something that they believed was not their fault. Other respondents expressed willingness to pay a sum of R150 (38%) and others a sum of R200 (6%).

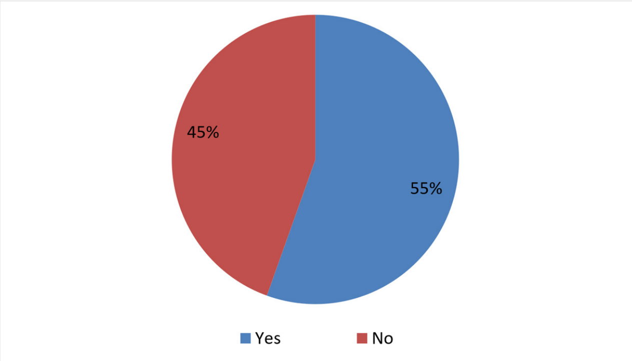

***Figure 9:** Households' willingness to pay for rehabilitation of the tailings facility*

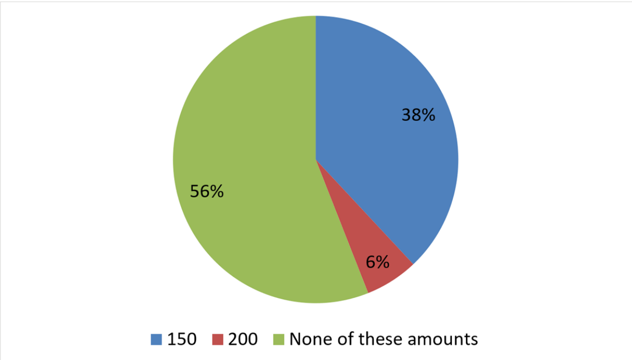

***Figure 10:** Households' amounts they are willing to contribute for rehabilitation of the tailings facility*

The challenge is exacerbated when a mine closes unexpectedly, and diminished growth and development are experienced. Numerous scholars have raised concerns about local communities, with regards to mine closure. The concerns focus on adverse environmental effects such as disintegrated infrastructure, river contamination, and dust generation (Andrews-Speed et al. 2005; Murray et al. 2005). Other scholars focused on social impacts such as crime increase, drop in the quality of life, people exiting mining towns and food insecurity (Botha et al. 2014; Marais 2013; McDonald et al. 2012; Rawashdeh et al. 2016; Rixen and Blangy 2016; Block and Owusu 2012; Ennis et al. 2014; Mengwe 2010; Ntema et al. 2017). It is evident that communities become vulnerable after sudden mine closure.

Summary

Despite the size of the mining industry, the direct and indirect environmental and socio-economic impacts are not clearly understood. Most research has focused on environmental impacts with a limited focus on the quality of life. Golder Associates (2003) note that possibly, the only accurate measure of sustainable development is quality of life, which is affected by many factors derived from Maslow's Hierarchy of Needs (Maslow 1954).

The hierarchy of needs of the gold mine village community appears to have been severely impacted by the liquidation of the gold mine. The results of the study indicate that the community feels that the biophysical environment is degraded through air pollution by dust and this poses health threats. The community perceives that environmental degradation occurs as a result of unrehabilitated TSF 6. The community also perceives the dispersed dust as a threat to their health and economic status. Furthermore, the community feels that their economic status is affected by medical expenditure to treat respiratory illnesses.

It is estimated that R890 million is the rehabilitation liability for the Gold Mining Company. Instead, only R34 million is available to address this problem (Golder Associates 2003). The community of the Gold Mine Village is not willing to pay for the rehabilitation of TSF6 and income is mentioned as their major barrier. Though the community in the mining village complains about the dust from TSF 6, it is likely that they will stay with the problem for some time is the mining company does not commit itself to solving the problem. This is because they are unable to pay for a rehabilitation fund for the tailings dump.

Anger, depression and anxiety were observed amongst the gold mine village community because of TSF6, and the sudden mine closure. TSF No.6 has been a major environmental problem for the Gold Mine Village ever since the mine liquidation occurred. People in communities such as this are exposed to nuisance dust as well as airborne dust through inhalation as well as ingestion. Particulate Matter has two inhalable fractions called PM_{10} and $PM_{2.5}$. These dust fractions are of interest since it can enter the lungs by way of inhalation, with the finer dust fraction ($PM_{2.5}$) able to penetrate deeper into the lungs. The biggest threat with the dust from TSF6 is that it is a receptor for toxic heavy metals which are part of the mining waste and is a nuisance for the community

Conclusion

The community perceives that conditions resulting from the unrehabilitated tailing dumps do affect their health, well-being and economic status. The gold mine village community has been unable, since 2013, to avoid breathing and ingesting the pervasive dust from TSF6. Although the South African mining regulatory frameworks and dust standards seem robust, compliance, management and mitigation strategies seem to be offset by conflicting regulations such as the NEMA, MPRDA with the Companies Act, 1973 and the Companies Act, 2008. The effects of these conflicts result in uncontrolled dust pollution from unrehabilitated tailings storage facilities, which poses threats to communities' health, well-being and economic status. In policymaking and development, all stakeholders need to meaningfully contribute, including governments, citizens, civil society and companies. This paper shows that socio-economic impacts will be different for each stage of a mining project, and not all impacts will occur at each stage. For example, in the case of the gold mine village community, the perception is that major environmental impact continues to affect the socio-economic status of the community, which is dust post sudden mine closure.

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Research article

Public perceptions of air quality status and suggestions for improvement: The case of Richards Bay and its surroundings, uMhlathuze Local Municipality, South Africa

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Abstract

Whereas industrial growth is instrumental in unlocking poverty and advancing development, often, the effect of pollution on the environment, particularly air quality, is seldom accurately predicted. The effects, which include mortality, morbidity, and loss of productive time, are demonstrated later after the damage is done. The views of the pollution-exposed public in industrialised centres is important to ascertain if policy intervention is enhancing environmental protection for all and justice by extension. Through an online survey, 215 residents of the rapidly industrialising Richards Bay and surrounding areas in South Africa responded to the questions about their perceptions of air quality and recommendations to improve air quality management. Results indicate a concern over air quality with most residents perceiving the air quality as fair or poor. Industrial emission was cited as the leading cause of pollution followed by sugar cane and agrarian burning. Irritation of the ear, nose and throat, as well as sneezing and coughing, were the health effects experienced by residents for which air pollution can be partly attributed. The public recommends an improvement in air quality monitoring, consequence management, technology and public transport system. In addition, they recommended the introduction of air quality offsets, incentives schemes, more public involvement, coordinated planning and better collaboration as a recipe for success in air quality management.

Keywords

Air quality, public perception, Richards Bay, South Africa

Introduction

Air pollution is a growing concern with an increasing number of acute air pollution events in many cities worldwide (WHO 2016). Both short and long-term exposure to air pollutants has been associated with health impacts with more severe respiratory impacts on the susceptible ill, children, the elderly, and poor people (Chiu 2013).

This is also the case in South Africa (DEA 2012) and by extension Richards Bay, where air quality has been a subject of discussion for some time due to previous pollution events in the area (Jaggernath 2013). With its known effect of aggravating lower respiratory tract infections, chronic obstructive pulmonary disease (COPD), ischemic heart disease (IHD), and cancers of the trachea and lung, air pollution is a concern for many people, particularly those living in and close to heavily industrialised areas (Jaggernath 2013).

To understand the extent of impact and to examine the question of environmental justice due to air pollution, whether inherent or implicit, it is crucial to obtain the views and gauge perceptions of the public.

This paper presents the results of a survey conducted in uMhlathuze Local Municipality, South Africa, and the surrounding areas. Respondents were asked whether they considered air quality to be good, bad, or fair and what impact it had on them. The respondents were also asked to suggest management actions that could enhance air quality.

Study rational

The knowledge of pollution perception and how best stakeholders can be adequately involved is essential to ensuring a progressive policy and in promoting environmental justice. This would support South Africa's imperative to protect public health as required in Section 24 of Chapter 2 of the Constitution of the RSA of 1996 which states that:

"Everyone has a right-(a) to an environment that is not harmful to their health or wellbeing: and (b) to have the environment protected, the benefit of present and future generations…"

Study area

Richards Bay, located within the uMhlathuze Municipality, is a growing metropolitan with several industries in relative proximity to residential areas (Okello and Allan 2015). The town is an economic centre and one of the country's strategic commercial hubs designated as an 'Area of National Economic Significance' (uMhlathuze Municipality 2016). In addition to the largest coal export terminal in the world and the second-largest port in South Africa, Richards Bay hosts several commercial, light, and heavy industrial activities such as paper, fertiliser and sugar production. With the Central Business District (CBD) as the main centre, the surrounding suburbs include Esikhaleni, Empangeni, Arboretum, Felixton, Mtunzini, Veld n Vlei and Enseleni. Figure 1 shows the local uMhlathuze Municipality, its industries and surrounding suburbs.

As of 2016, the area had a population of 410 465 (Stats SA 2016) and covers an area of 1233.3 km² (Cogta 2017).

An overview of air pollution in Richards Bay

The highlight in terms of air pollution was in 1994 when an emission incident at the Indian Ocean Fertilizers (now Foskor) led to the evacuation of the central business district and resulted in a fatality. This incident spurred public pressure and led to a petition and consequently the formation of the Richards Bay Clean Air Association (RBCAA), which was spearheaded by ordinary concerned residents (Okello and Allan 2015; Savides 2011).

The RBCAA has played a vital role in documenting the history of air quality in Richards Bay through monitoring and reporting. The most important history comprises data collected from its network of stations for over 20 years. This has enabled trends to be established; most recently in 2018 where ambient Particulate Matter (PM_{10}) and Sulphur Dioxide (SO_2) have shown a decreasing trend although not significant (Okello et al. 2018). Industry plays a significant role in the air quality makeup of the area: for example, a sharp decrease in SO_2 post-2014 coincides with the closure of Bayside Aluminium and Tata steel (Okello et al. 2018).

Aside from the ambient concentration data, trends in complaints recorded by the RBCAA over the last two decades was critical in

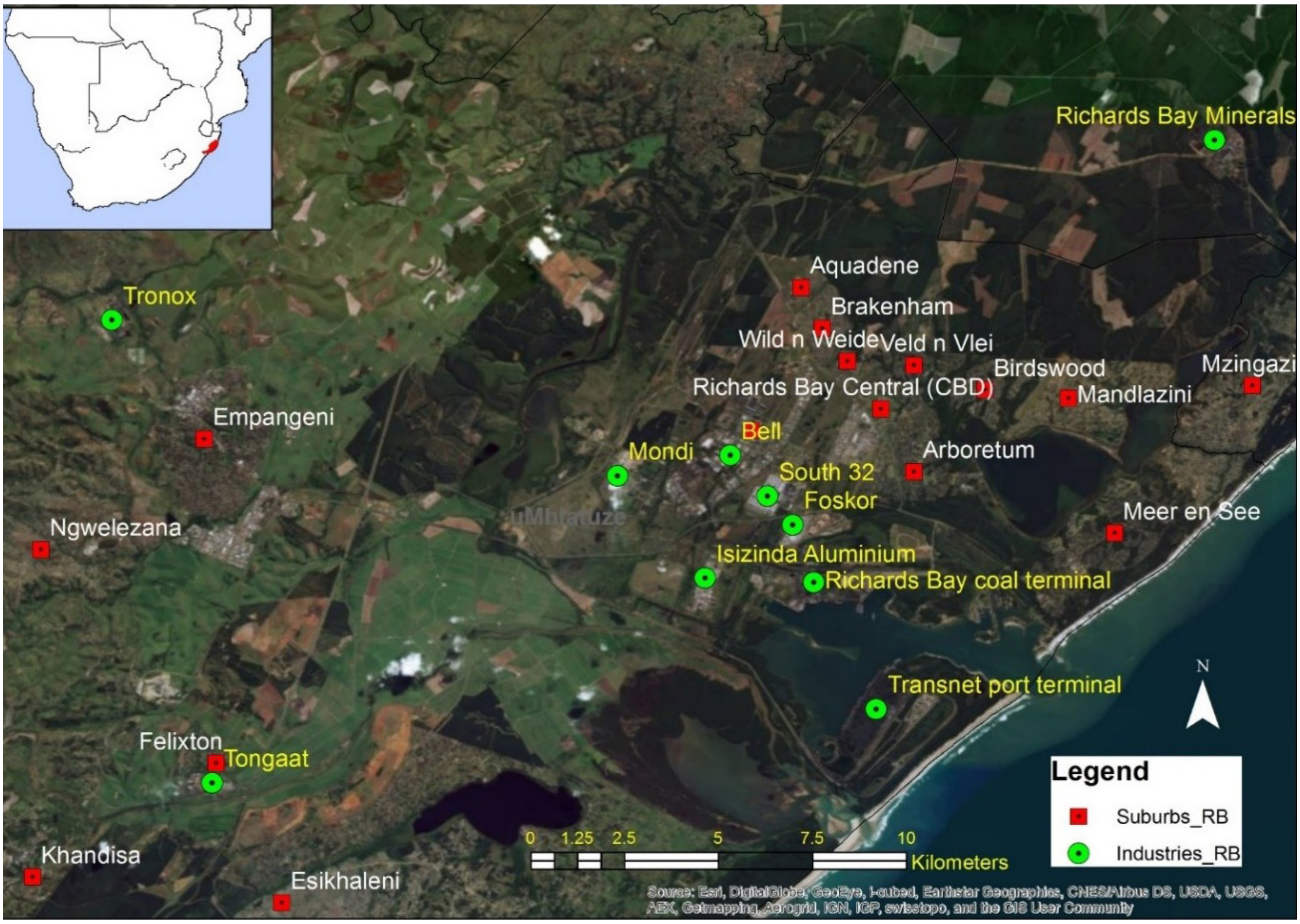

***Figure 1:** Richards Bay industries and surrounding suburbs within the local uMhlathuze Municipality (Okello, Okello, and Zunckel 2020)*

assessing the historical changes of air emissions. The association recorded a total of 3,638 complaints between the years 2000 to 2017, most of which were attributed to industries around the CBD (RBCAA 2018). The maximum number of complaints received in a single year was 397 in 2004, this reduced to approximately 200 between 2010 and 2015, and decreased gradually to 100 in 2017 (RBCAA 2018). The reducing trend of complaints can provide a view of pollution incidents over the years.

Legal and policy context of air pollution

The National Environmental Management: Air Quality Act (NEM: AQA) was partially enacted on September 9, 2005, and fully enacted on April 1, 2010. NEM: AQA repealed the Atmospheric Pollution Prevention Act (APPA) which had been enacted in 1965. Subsequently, the National Ambient Air Quality Standards (NAAQS) covering priority pollutants such as particulate matter, sulphur dioxide, nitrogen dioxide, carbon monoxide, lead, ozone and benzene were formalised on December 24, 2009. Similarly, Minimum Emission Standards (MES) for Listed Activities, i.e., significant industrial facilities, were developed and were first gazetted on March 31, 2010. These were then amended both in 2013 and 2015 and more recently in 2018 for selected activities. The influence of these policy instruments and their reduction of risks associated with air pollution is a subject that is slowly but receiving attention, and more studies on this subject are required.

Methodology

Overview of methodology / data collection

The study utilised Evasys online survey system to gather data. Evasys was selected because of its relative ease in formulating questions and disseminating surveys. Over recent decades, electronic surveys have become increasingly common due to the strong advantages of speedy distribution and response cycles (de Bernardo and Curtis 2013; Koitsalu et al. 2018; McMaster et al. 2017). The other benefit is that costs per response decrease significantly as sample size increases (Scott et al. 2011). Moreover, an online survey is dynamic and can provide statistical results on an immediate basis (Yun and Trumbo 2000).

Although the use of the internet is growing very rapidly, it is not universal (Phokeer et al. 2016). Many citizens still do not possess internet facilities, especially older people and those in lower-income and education groups. Therefore, online surveys may not fully reflect the views of the entire population, which poses a challenge in generalising results (de Bernardo and Curtis 2013). According to Statistics SA, about 61,8% of South African mostly in urban area households had at least one member who had access to or used the Internet either at home, work, place of study, or internet cafés (Stats SA 2018).

Further, respondents may dislike unsolicited e-mails or too many emails perceiving this as an invasion of their privacy and thus may decline to respond (de Bernardo and Curtis 2013; Marra and Bogue 2006).

The eight critical steps taken from planning to survey delivery and, eventually, data collection to ensure that the survey process yielded the desired results are shown in Figure 2. These steps are described in detail in the following sections.

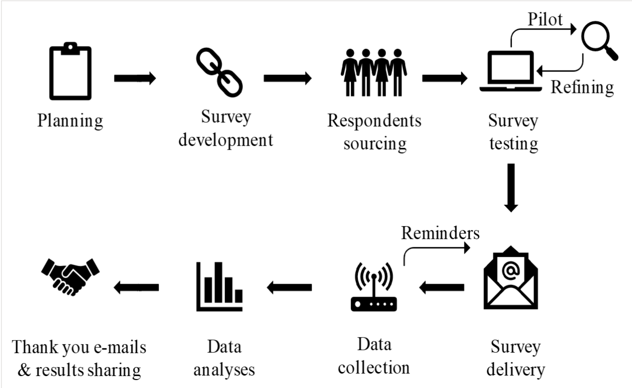

Figure 2: *Steps taken during online data collection*

Planning (sample size determination, selection criteria) and respondents sourcing

Sample sizing in qualitative research is a matter involving judgment against the quality of information required, the sampling strategy and the research product intended (Sandelowski 2000). There is no 'magic number' (Neuman 2014). Nevertheless, the sample size was determined using equation 1 below adopted from the University Hospital Bristol (University Hospital Bristol 2018).

$$n = \left(c2Np(1-p)\right) / \left(\left(A2N\right) + \left(c2p(1-p)\right)\right) \quad (1)$$

n is the sample size required

N is the whole target population in question

p is the average proportion of records expected to meet the various criteria (1-p) is the average proportion of records not expected to meet the criteria

A is the margin of error deemed to be acceptable (calculated as a proportion), e.g., for 5% error, either way, A = 0.05

C is a mathematical constant defined by the Confidence Interval chosen, i.e. (confidence level). At 95% confidence level c = 1.96; at 90% c = 1.645; and at 80% c = 1.28

For this study, the following parameters were used:

N 410 465 population (Stats SA 2016)

p 70% expected incidence

A 0.05 accuracy

c 1.645 (90% confidence). The confidence level was chosen as opposed to 95% to cater to the uncertainty of sampling method (online survey) but also a high level of the population not represented in the sample due to age groups omitted.

Based on the above, the sample size (n) was determined to be 228. The survey was sent out to 325 individuals (higher than the calculated sample size). In general, the larger the sampling population, the smaller the bias that would normally come from a single group (Iarossi 2006).

The respondents were sourced using a combination of non-random purposive sampling and chain or snowball sampling approach (Neuman 2014; Patton 1990). In purposive sampling, the target sample population is selected based on some criteria and specific purpose in mind. For this research, a respondent had to be an adult of 18 years or older, current or previous resident of the uMhlathuze Local Municipality, and have an e-mail address to access the online survey. According to Neuman (2014), a researcher may use purposive non-random sampling in 3 cases which include: to select unique cases that are specifically informative, to select members of a difficult-to-reach population, and where the researcher wants to identify types of cases for in-depth investigation.

Chain sampling, on the other hand, is a multistage technique that begins with one or a few people or cases and spreads out based on links to the initial cases (Neuman 2014). Respondents were initially identified from neighbourhood and sports groups, databases of the RBCAA, and groups that had previously requested to be included in various environmental impact assessment studies within the local uMhlathuze Municipality. More respondents were then identified by the initial group who provided additional contacts and spread the request to be involved, a method referred to as snowballing (Neuman 2014).

Precautions to improve response rate and quality of results

As part of survey preparation, ethics approval was obtained from the University of Free State Faculty of Agricultural and Natural Sciences. Besides protecting the respondents and the researcher, ethical review demonstrates adherence to accepted ethical standards of a good research study. This has been shown to increase recruitment potential (Newson and Lipworth 2015).

Care was taken to assure the respondents of anonymity and confidentiality of their responses. The number of questions was minimised, and their complexity reduced to simplify the response. According to Iarossi (2006), sensible questions and sensitivity in administering surveys improved the quality of results dramatically.

Also, an estimate of the time to complete the survey was provided to prepare respondents and avoid any premature opt-outs. To prevent multiple responses on one survey link, the survey was set up to be used only once. As such, a new survey had to be sent to a new respondent.

The questions in the survey were both closed and open-ended to maximise on comments from the respondents.

Pre-testing and calibration of the survey instrument (pilot survey)

The online survey instrument was first checked for internal coherency, proper wording, proper answer sets, and logistical clarity and duration of the survey.

A small group of respondents was selected and asked to test the survey. Comments received from the group related to spelling and grammatical errors, difficulty in understanding some questions, and suggestions on additional questions that could add value to the survey. These comments were incorporated into the survey to improve it before it was distributed to respondents.

Survey delivery and data collection of results

Survey invitations containing the survey link was sent to selected respondents via e-mail. An introduction explaining the purpose of the survey and confidentiality preceded the questions. A period of one month was given for response collection.

Responses were then monitored for two weeks, after which a first survey reminder was sent to the respondents. To increase the response rate, a second survey reminder was sent a week later. The second reminder was sent only to respondents who had not completed the survey as determined by the Evasys online survey system.

The responses downloaded from the Evasys survey system was checked to determine their validity after which analysis was done. The response rate was calculated using equation 2 below:

$$Rr = \frac{R}{n} x\ 100 \qquad (2)$$

Rr is Rate of response
R i s the number of the actual responding population
n is the number of the sampled population

As a qualitative study which deals more with people's perceptions and behaviour as opposed to quantities, descriptive analysis was used to examine the results. (Ashley, Boyd, and Boyd 2006; Neuman 2014).

[1] Chain sampling is a technique where existing study subjects recruit more subjects from among their acquaintances for a researcher (Neuman 2014; Patton 1990).

Results and discussion

In this section, the respondent's characteristics and their perception of the status of air quality, the sources of pollution and impacts thereof as well as involvement in decision making are examined. Importantly, the suggestions and recommendations for improving air quality management are also presented and discussed.

Respondents characteristics

Two hundred fifteen respondents (215) out of 325 who were sampled completed the questionnaire. This represented 13 respondents less than the determined sample size considered adequate to generalise the results. However, this equates to a response rate of 66.2%, which is very high for a survey (de Bernardo and Curtis 2013; Marra and Bogue 2006). The respondents comprised 64% male and 36% female. All respondents were above 18 years, with the majority older than 30. Respondents were drawn from different occupations and sectors of the Richards Bay economy, with close to 65% from the private sector.

Spatially, the respondents were distributed throughout the uMhlathuze Local Municipality with the majority coming from Merensee (35.3%), Arboretum (15.3%), Birdswood (6.5%), Veld n vlei (5.1%), Empangeni (7.4%), Esikhaleni (4.7%) and Brakenham (4.7%) constituting the majority.

Public perceptions of air quality status in uMhlathuze Local Municipality

Most of the respondents ranked air quality in uMhlathuze Local Municipality and surrounding as either fair (40%) and poor (just over 30%) (Figure 3). Thirty percent of the respondents thought that the air quality was either good or very good (Figure 3).

When asked if they considered air pollution as a problem within the Local Municipality, close to 80% agreed, of which 30% strongly agreed. The main manifestation of pollution was reported as dust deposit and smell in residential areas close to industrial sources such as Arboretum and CBD. These results mirror the trends of PM_{10} and SO_2 where areas such as the CBD, Arboretum, Brakenham, and areas around the Richards Bay Harbour were deemed to be most impacted by air pollution (Okello et al., 2018).

Sources of pollution and impacts thereof

When asked about their perceived top three air pollution sources in the area, over 80% of the respondents pointed to the industry as their number one source. This was followed by the burning of forests and sugarcane (51% of respondents). Motor vehicle emissions were selected as the third biggest cause of pollution (Figure 4).

Regarding the actual impacts of air quality, seventy percent (70%) of the respondents indicated that they were impacted negatively in one way or another by pollution. Twenty percent (20%) did not know whether pollution had any effects on them

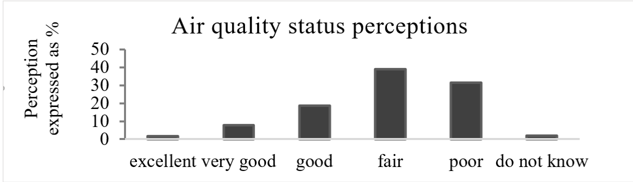

Figure 3: *uMhlathuze Local Municipality air quality perceptions expressed as a percentage of the total respondents*

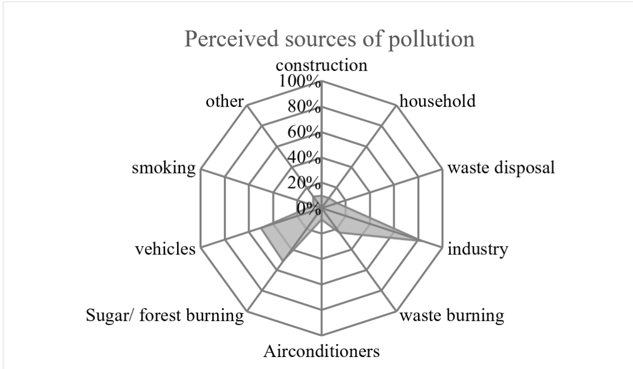

Figure 4: *Perceptions on primary sources of pollution in and around uMhlathuze Local Municipality*

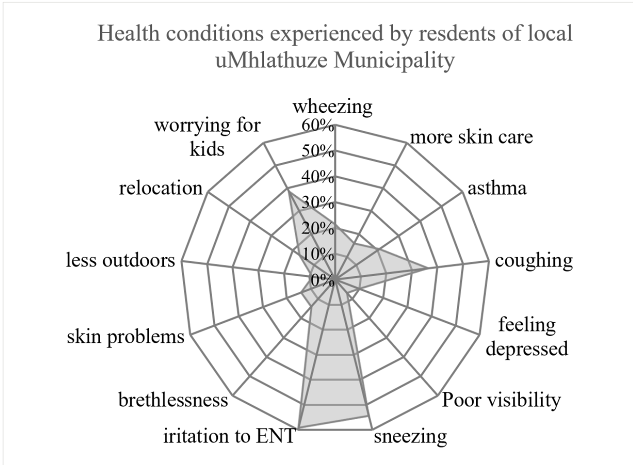

Figure 5: *Health conditions experienced by residents for which air pollution can be partly attributed*

or not, potentially indicating a resigned or just an unaware part of the population. The impact was only a little to about 50% of the respondents impacted, while 15% were strongly impacted. The specific impact that was felt by most respondents (close to 60%) was the irritation of the eyes, nose, and throat (ENT). Respondents also highlighted sneezing (55%) coughing (36%), wheezing, and asthma incidents (20% each). About 48% of the respondents indicated that they worried about their children (Figure 5).

These results are similar to those of a previous study in Richards Bay (Jaggernath 2013). Other impacts identified included nuisance dust or ash, which often resulted in increased cost of clean-up of swimming pools, cars, and household items including clothes. It was indicated that the effects occurred mostly during the evening, the night and morning hours. Often, the economic cost of clean-up of pollution is not quantified but is vital in determining the real pollution effects to those impacted (Stoerk 2018).

Concerns over frequent wind-blown coal dust and odorous emission that cause the burning of eyes and irritation of the throat were reported in the Arboretum and Alton areas. Suburbs such as Merensee were less polluted due to their distance away from industrial sources and probably due to the shielding effect of wind blowing from the sea. More so, several respondents indicated that they have on several occasions, had to visit the hospital due to breathing difficulty. Some pointed out that they had more respiratory issues during their stay in Richards Bay, compared to previous less polluted areas.

Public participation in air quality management

A set of questions was aimed to ascertain the level of knowledge and extent of participation in air quality-related matters, including management thereof.

Knowledge of legislation, particularly by impacted parties, is important in ensuring effective policy implementation (Craig et al., 2008). When asked whether they understood the legal requirements for air quality management in terms of the National Environmental Management Air Quality Act, over 60% of the respondents indicated that their knowledge of legislation (pollution control framework) was either good or very good although 30% did not know or had little knowledge of the legal framework. A respondent contended that while the relevant air quality guidelines and laws are useful, enforcement is weak, and no meaningful action is taken when offences are identified.

Regarding knowledge of where to channel their complaints, 73% of respondents indicated that they knew they could complain about bad or poor air quality through the uMhlathuze Local Municipality or through the RBCAA, which they said was instrumental in monitoring pollution levels in the area.

Over 50% of the respondents disagreed with the notion that pollution was out of their control and that they cannot do anything about it. Twenty-three percent of the respondents strongly disagreed that they were powerless. This indicates a society willing to engage. Over 90% of respondents believed that they would act in one way or another if they knew how best to contribute to cleaner air and that improving the environment is the responsibility of all citizens.

This thread of public knowledge, particularly in highly polluted areas, is somehow common, probably due to the felt impact.

Interestingly, over 75% of the respondents either agreed or strongly agreed that the government should do more to promote and encourage a better environment, even if taxes go up slightly. The 25% who strongly disagreed that their taxes should not be increased indicated that the government had more than enough resources.

Practical suggestions/ options for improving air quality management and policy

During the survey, respondents were asked to state their opinion on how air quality management could be improved. The improvement options have been grouped into eight main categories that include:

1. Air quality monitoring;
2. Law enforcement, consequence management;
3. Technology and research development;
4. Air quality offsets and incentives schemes;
5. Environmental taxes;
6. Improvement in public transport;
7. Public participation; and
8. Coordinated planning and collaboration.

Air quality monitoring

Data from continuous monitoring of air pollution is one of the most essential parameters in ascertaining the efficacy of policy intervention. This enhances the implementation and enforcement of environmental (Jin, Andersson, and Zhang 2016)). To store data and make it available for use, a single data repository system similar or same as the RBCAA or the South African Air Quality Information System (SAAQIS) was suggested. About 10% of respondents indicated that independent air quality monitoring by organisations such as the RBCAA plays a critical role in data provision, publishing complaints, their sources, and resolution.

Also, it was recommended that both human and technical capacity at the local uMhlathuze Municipality and RBCAA should be supported with funding and enhanced to accelerate and expand monitoring.

The local uMhlathuze Municipality was commended for ambient air quality monitoring but urged to share data and extend monitoring to other forms of pollution nuisance pollution such as public smoking in restricted areas, smoking vehicles, and agricultural burning (sugar and forestry).

Law enforcement and consequence management

Law enforcement and monitoring of compliance with standards and legislation featured prominently on the responses. Broadly, a well-managed, visible, and frequent enforcement regime is crucial to ensuring success in policy implementation (Craig et al. 2008; Stoerk 2018). In Taiwan, for example, an inspection and enforcement program expanded to cover more than 10,000 factories resulted in significant emission reduction (Shu-Hwei Fang and Hsiung-Wen Chen 1996).

Stringent penalties should be applied with caution to polluters as a way of enforcing the legal requirement. Examples of penalties provided from the survey included: directives to immediately remedy pollution, appropriate fines where negligence is determined, and at the worst withdrawal of license to operate and prosecution.

These measures have been applied elsewhere (Bondy, Roth, and Sager 2020; Kondrat 2000) and are provided for in the legal framework of South Africa. For example, Section 28 of the National Environmental Act (Act 107 of 1998) (NEMA) (Republic of South Africa, 1998) bestows on the polluter the duty to take reasonable measures to prevent significant pollution or degradation of the environment from occurring continuing or recurring (Xiaobo and Jianwei 2015). While legislation is considered adequate for industrial pollution control, the burning of sugarcane is not regulated in terms of the NEM: AQA.

Nevertheless, the Provincial Department of Environmental Affairs (DEA) has developed guidelines for the burning of sugarcane in KwaZulu-Natal (uMoya-NILU 2014). According to uMoya-NILU (2014), within this guideline document is the Sustainable Sugarcane Farm Management System (SuSFarMS), a voluntary self-audit tool aimed at municipalities and sugarcane farms to minimise the air pollution impacts of sugar cane burning. These guidelines should perhaps be legalised.

Technology and research development

Prevention of pollution from the source was far much desired than remedying the effects. Comments were made for industries to embrace new technology in pollution prevention, monitoring, detecting pollution leak sources and predicting potential failure of equipment. A wide range of air pollution control devices can be used to reduced air pollution and in turn, prevent their adverse effects on the environment and human health (Kalender 2019).

Additionally, inadequate and non-timeous maintenance was cited as a cause of low equipment reliability, availability, and unnecessary failures with possible pollution effects.

It is worth noting that post-2010, it was a mandatory requirement in most of the industrial Air Emission Licences (AEL) to undertake point source emissions measurements either continuously or periodically. This alongside the requirement to have leakage detection on pollution prevention equipment is good practice in reducing potential sources of pollution.

More so, it was recommended that technology sourced should consider appropriate waste disposal mechanisms commensurate to local legislative requirements. This is in order not to create another environmental problem.

Air quality offsets and incentives schemes

Respondents in the survey encouraged industries to show active investment to offset their contribution to any form of pollution and to meet and exceed the regulated standard. Relatively inexpensive and easy to implement methods such as planting trees around factory premises to reduce wind-blown dust was suggested. Offsets have been used to encourage 'good deeds' where abatement to the desired standard is a challenge to achieve (Langerman et al., 2018). This has been the case in South Africa where the air quality offsets guidelines in terms of the NEMA: AQA (DEA, 2016b) gives credence to offsets. The guidelines define offsets as:

"An intervention, or interventions, specifically implemented to counterbalance the adverse and residual environmental impact of atmospheric emissions to deliver a net ambient air quality benefit within, but not limited to, the affected airshed where ambient air quality standards are being or have the potential to be exceeded and whereby opportunities and need for offsetting exist"

Examples include investments in switching households to cleaner energy sources, low emission appliances, and insulation; reducing domestic waste burning and emissions from landfills (ESKOM, 2016). In this context, offsets can be used to deliver a positive net improvement in air quality (Langerman et al., 2018). While this may be an opportunity for improvement, care should be taken to ensure that abatement precedes the offsetting of pollution.

Regarding incentives, to encourage companies to perform better and to recognise cleaner practice, it was suggested that an incentive scheme for good air quality should be established for the region. This can include air quality awards, best abatement practice engineering prize, best air quality initiative award, etc. This would not only encourage the sharing of good practice but would also promote awareness and focus on investment to tackle adverse emissions and promote the implementation of new technology by industry (Di Falco 2012; Gerhardt 2006; Levin 1990).

Environmental Taxes

Application of environmental taxes for pollution prevention is a way to internalise pollution costs, thus shifting the burden to the pollutant and reducing the cost to society (Di Falco 2012). In South Africa, industries pay a prescribed fee for their Air Emission Licences (AEL) as required in terms of the NEMA: Air Quality Act (Act No39 of 2004). However, this is paid once-off during application and renewal after five years and thus does not constitute a pollution tax. Nevertheless, the fuel levy and the proposed carbon tax aimed at reducing carbon footprint are examples (Alton et al. 2014; National Treasury 2018). These, in time, might and should probably be considered among other remedies to reduce priority pollutants such as SO_2, NO_2 and PM. This sort of taxation will require an improved and stringent monitoring accuracy and should be balanced not to be an economic growth burden (Chen and Liu 2009; Di Falco 2012).

Improvement in public transport

Vehicular emission within the uMhlathuze Local Municipality cannot be ignored and is considered the third-largest source of emissions by the residents. This will become even more pronounced given the projected industrial as well as population growth. In just over five years between 2011 and 2016, the population increased by over 22% ((uMhlathuze Municipality 2018). To this end, suggestions were made to design a public transport system that encourages commuters to use public transport rather than private vehicles. A good example is to integrate safe bicycle routes to encourage cycling. A study determined that by cycling, one would gain 3-14 months of life compared to the risk dying from road traffic accidents (5-9 days lost) and exposure to pollutants (0.8-40 days lost) (de Hartog et al., 2010; Rojas-Rueda et al., 2011). In Stockholm, Sweden, cycling saves 449 years of life annually by reducing vehicle emission and thereby limiting population exposure (Almström et al., 2017).

In addition to enhancing the design of public transport, it was also suggested that more vigorous enforcement against unroadworthy vehicles and compromised older vehicles would improve ambient air quality.

Public participation

To improve air quality management, it was suggested that more public awareness of the effects of pollution and how to identify pollution was necessary. This is obvious (Bdour et al., 2008; Chompunth, 2013) and should also include awareness on the impacts of household and outdoor air pollution particularly in the low-income areas. A suggestion was made to have a section on print media where an indication of the air quality status and details of people to contact can be published. In this section, it was also suggested that complaints and resolutions thereof could also be published.

On this, the public was encouraged to complain whenever they experienced air pollution events or whenever they saw it. The government, on the other hand, should have a portal/application where air quality complaints can be lodged. These complaints should be followed up with prompt feedback to encourage more public participation. The RBCAA has shown that proper complaints handling system works and encourages more public participation (Okello and Allan 2015). Transparency in terms of emission data provision, accountability for pollution sources, and collaboration between different role players are cited as pillars for success and promotion of justice (Li et al. 2018).

Being a process that facilitates decision making, the public was encouraged to take part in the Environmental Impact Assessment of new projects and specifically ask about air quality impacts. Comments made during the environmental authorization processes in other jurisdictions have been shown to provide desired emission reduction by incorporating and improving monitoring requirements and ensuring that pollution abatement is in place (Chompunth, 2013; Jin et al., 2016). Relevant officials of the local and district municipalities were encouraged to continue taking part in, and comment on environmental authorisation applications as the municipality plays a key role in planning development.

Coordinated planning and collaboration

Town planning considerations can mitigate air quality impacts on people and the environment (Zhou, Li, and Wang 2018). It was suggested that as much as possible, industries and residential areas should be separated. This would limit exposure. Another measure suggested was to limit approvals of industries with high potential for air pollution. This should be implemented if it is determined that air quality has reached health thresholds in terms of national ambient air standards and specifically where a proposed industry does not have or show adequate pollution prevention measures.

On collaboration, it was suggested that the government should consider working with the well-established NGO associations such as RBCAA to conduct ambient air quality monitoring. The RBCAA works on a polluter pays model with the involvement of industry and other stakeholders. The forum would be an already available channel for the law enforcer to work hand in hand with the industrial sources of pollution for the benefit of all and the improvement of the affected airshed. Potential areas of collaboration may include offering financial support to cater for the cost of monitoring or joint monitoring and database and information management. This would save not only money but also time and will ensure efficient use of personnel and resources.

Conclusion and recommendations

The results of the survey indicate a concern over air quality. Although progress has been made in reducing pollution, much is still required to achieve the desired state of protection contemplated in Section 24 of the RSA constitution.

Most of the public perceive the air quality as fair or poor. The fair rating is likely to be as a result of a downward trend in pollution, particularly PM_{10} and SO_2 (Okello et al., 2018). Nonetheless, widespread sporadic pollution events over the airshed continue to occur. Residential areas closer to main pollution sources such as CBD and Arboretum seem to experience more pollution effects.

The leading cause of pollution impacting the area residents was industrial sources followed by agricultural (sugar cane and agrarian burning) and then general waste burning. These results are similar to previous studies and reports in the area (Jaggernath 2013; uMoya-NILU 2014) and point out to where the focus should be if further pollution reduction is to be achieved.

Perhaps because of the exposure to pollution, and probably awareness campaigns, one would say the public appear to be very knowledgeable of air quality issues and particularly the air quality legislation. This knowledge may be a result of most of the population sampled being educated. A survey of the more rural, less formal sectors of the population may reveal a different result.

Nonetheless, the myriad of views expressed by the public in uMhlathuze Local Municipality regarding possible improvement is an important step in providing input to air quality management in the Municipality, in South Africa and other countries facing similar challenges. More specifically, an improvement in air quality monitoring, consequence management, use of environmental taxes, appropriate technology, and the public transport system is key for air quality management. More so, the introduction of air quality offsets and incentive scheme would encourage good practice. The public wants to be involved and have cited coordinated planning with better collaboration as a recipe for success in air quality management.

In terms of future research, a similar survey of the perceptions of the population living in more rural areas and could be conducted. This could be expanded to the whole country given that an online survey is relatively easy to distribute. Lastly, health impacts studies are key to test the reliability of implemented intervention and could form future research areas.

Acknowledgement

We would like to thank the residents of the City of uMhlathuze for taking the time to respond to the survey and expressing their opinion on how air quality management in the area could be improved. Your responses form the fabric of this paper. We would also like to thank the Richards Bay Clean Air Association, particularly Sandy Camminga, for sharing the RBCAA's database for the survey distribution. This database greatly enhanced the response received.

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Technical article
Using Microsoft© Power BI© to visualise Rustenburg Local Municipality's Air Quality Data

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Abstract
Microsoft© Power BI© is a business analytics tool that visualises data in an accessible manner. It creates visual data reports quickly in a series of panels to give an overview of data while still offering access to more sophisticated visualisation methods too. While statistical tools, like R and MatLab, remain the 'gold standard' for analysing air quality data, simple methods to visualise data are also helpful. Here, we explored the use of Power BI Desktop© to visualise and interpret air quality data for the Rustenburg Local Municipality. Rustenburg is in the Waterberg-Bojanala Priority Area – the third air pollution priority area for air quality management. Ambient PM_{10} data for three towns, namely, Thlabane, Marikana and Boiketlong, were obtained for six years (2013-2018) in South Africa. Data underwent quality control before being imported into Power BI©. A four-panel dashboard was generated to show (in) compliance with the daily and annual average South African National Ambient Air Quality Standard for PM_{10}, annual and average concentrations, frequency of exceedances and a summary of data availability by site. Generally, PM_{10} data quantity and quality were poor and where data were available, concentrations were high. This type of data visualisation tool can be applied with relative ease by Air Quality Officers and Environmental Health Practitioners for a snapshot overview of the air quality in their area of jurisdiction. The interactive dashboard is also useful for making graphics for policy documents and reports.

Keywords
air pollution, environmental health, South Africa, Waterberg Priority Area

Introduction

Air quality in the Waterberg-Bojanala Priority Area
The Waterberg-Bojanala Priority Area was declared as such on the 15 June 2012 (DEA, 2012). It is in the north-west of South Africa and covers about 68 000 km^2, lying on the Bushveld Igneous Complex, characterised by significant mining and metallurgical activities (Venter et al. 2012). It includes the Waterberg District Municipality in Limpopo and parts of the Bojanala Platinum District Municipality in North West Province. Nine Local Municipalities are located within the Priority Area one of which is Rustenburg.

The Priority Area was identified as a potential air pollution hotspot at a time when several developments in the area were being planned. A precautionary approach was taken to manage and control air quality simultaneously to the planning of these developments.

Local sources which influence the air pollution in this region include traffic along the N4 platinum highway, mining and industrial sources as well as, to a large degree, domestic fuel burning practices (Hirsikko et al. 2012, Venter et al. 2012, C&M Consulting 2019). Sources contributing to the particulate matter (PM) concentrations in the region have been shown to stem from domestic burning for heating and cooking in the early mornings and the late afternoons / early evenings. During the day, PM has been found to originate from industrial, residential and natural sources (Hirsikko et al. 2012).

Power BI

Local and provincial-level Air Quality Officers, Environmental Managers and Environmental Health Practitioners are tasked to monitor and manage air quality in the Waterberg-Bojanala Priority Area. This work is demanding as it is part of a large scope of work, usually covering a wide spatial area of jurisdiction, and with insufficient resources and capacity, and so finding relatively easy and simple tools to interrogate and present air quality data, in a way that is easy to understand, is useful.

Microsoft© Power BI© (BI, Business Informatics) is a business analytics tool that visualises data in an accessible manner. It transforms data into visuals which one can readily share on any device. It compiles single view, multi-panel displays for quick decision-making and interrogation of data (Power BI© is available at the following website https://powerbi.microsoft.com/en-us/). Other tools to analyse air quality data do exist, such as OpenAir, R, Statistica, MatLab, or Python. Advantages of using Power BI© however, are the integration with other Microsoft© products such as Excel© in which air quality data is often made available. It also presents the data in a dashboard format that is 'less scientific' and possibly useful for display in a policy document or report.

In this report, we explored the use of Power BI© to visualise and interpret air quality data for PM_{10} from 2013-2018 for the Rustenburg Local Municipality. We illustrate the dashboard and the nature of the graphics that the software can present and, in so doing, attempt to interrogate the trends in PM_{10} for the Municipality.

Methods

Data

Six years (2013-2018, inclusively) of PM_{10} data were available from three stations, namely, Thlabane, Marikana and Boiketlong, which form part of the of the Rustenburg Local Municipality Air Quality Monitoring Network. Data were provided at 1-hour intervals as well as daily averages. Analyses were made using the daily average datasheets.

PM_{10} data were analysed (using the 99th percentile) to determine annual average and annual maximum concentrations in µg/m^3 between 2013 and 2018. Annual and daily compliance to the South African National Ambient Air Quality Standards (NAAQS) was also assessed. Exceedances above the daily limit value (defined in the NAAQS) were also calculated, together with the percentage of time that the concentrations were above these limits (based on data availability).

Table 1: *Summary of daily PM_{10} exceedances, data availability, annual average- and daily maximum concentrations by year, i.e. 2013 to 2018 for Rustenburg Local Municipality.*

Station name	Year	Annual average PM_{10} (µg/m^3)	Limit value annual (no exceedance allowed)	Limit value daily (µg/m^3)	Maximum daily average concentration (µg/m^3)	Daily limit exceedances (allowed 4)	% time over limit (relative to data available)	Data availability (%)
Marikana	2013	53.55	40	75	118.83	38	22.89	45.48
	2014	47.03	40	75	116.05	40	15.15	72.33
	2015	39.42	40	75	91.98	2	4.17	13.42
	2016	54.82	40	75	116.72	1	11.11	2.47
	2017	No data	40	75	No data	No data	No data	No data
	2018	74.14	40	75	195.91	91	39.39	63.29
Boiketlong	2013	35.21	40	75	107.03	1	1.12	24.38
	2014	71.95	40	75	231.90	79	35.43	61.1
	2015	37.44	40	75	60.59	0	0	3.56
	2016	No data	40	75	No data	No data	No data	No data
	2017	No data	40	75	No data	No data	No data	No data
	2018	31.41	40	75	54.95	0	0	5.47
Thlabane	2013	67.08	40	75	143.86	100	40.76	65.21
	2014	42.87	40	75	184.04	1	4.76	5.75
	2015	35.67	40	75	75.07	2	6.25	4.38
	2016	35.69	40	75	81.15	1	0.01	17.81
	2017	30.29	40	75	71.38	0	0	6.03
	2018	13.89	40	75	55.64	0	0	4.38

Application

Data were prepared and checked for availability as well as other quality control measures in Microsoft© Excel© using pivot tables and then by importing structured sheets into Power BI© using their user-friendly dashboard interface. Bing is integrated into the application for the manufacturing of maps to plot air quality monitoring station location information, for example, whether the station complies with the NAAQS for PM_{10} in a particular year.

Results

Table 1 gives a summary of the PM_{10} data that were provided by Rustenburg Local Municipality between 2013 and 2018. Data availability was a challenge for all three ambient stations. No data were available from Boiketlong station from 2016 to 2017 (inclusively), and from Marikana in 2017. Marikana station had the best data availability in 2014 at 72%.

The annual average maximum PM_{10} concentrations, between 2013 and 2018, were 74, 72 and 67 µg/m³, for Marikana, Boiketlong and Thlabane, respectively. During the six year-period assessed, Marikana showed exceedances of the annual NAAQS (40 µg/m³) four times, Thlabane twice and Boiketlong once. The daily NAAQS for PM_{10} is 75 µg/m³ and in some places this limit was exceeded multiple times during a year. For example, in Thlabane, this limit was exceeded 100 times in 2013. Moreover, in some years, the percentage of time that the PM_{10} concentrations were above the daily limit value (depending on data availability) was up to 40% at some stations.

These data and results were then visualised in a dashboard using Power BI©. Figure 1 shows the panel-type display and it indicates that two out of the three stations did not provide enough data to draw a conclusion about compliance with the PM_{10} annual average limit for 2018. The plot on the top-right hand-side of the dashboard succinctly shows the maximum annual average concentrations for PM_{10}, as well as the number of times a respective station showed non-compliance with the annual NAAQS within the time under review. The bottom left-hand-side plots shows the number of daily limit value exceedances while the table on the bottom right emphasises the problem of data availability.

Discussion

From the evidence available for PM_{10} concentrations in the Rustenburg Local Municipality at three monitoring stations, it is apparent that air PM_{10} concentrations often exceed levels considered by the NAAQS as "safe to breathe". The NAAQS annual and daily limits are not being met most of the time. There is some variability in the data reported by different studies. Data collected in August 2008 showed that daily PM_{10} concentrations at Marikana ranged between 3 – 9 µg/m³ (Kaonga and Kgabi, 2011). Venter et al (2012) monitored PM_{10} concentrations just half a kilometre south-east of the monitoring station set up by the Rustenburg Local Municipality in Marikana and reported a maximum 24-hr average PM_{10} concentration of 222 µg/m³. Similarly, the 2019 August report of the Rustenburg Local Municipality's Ambient Monitoring Network, for the time

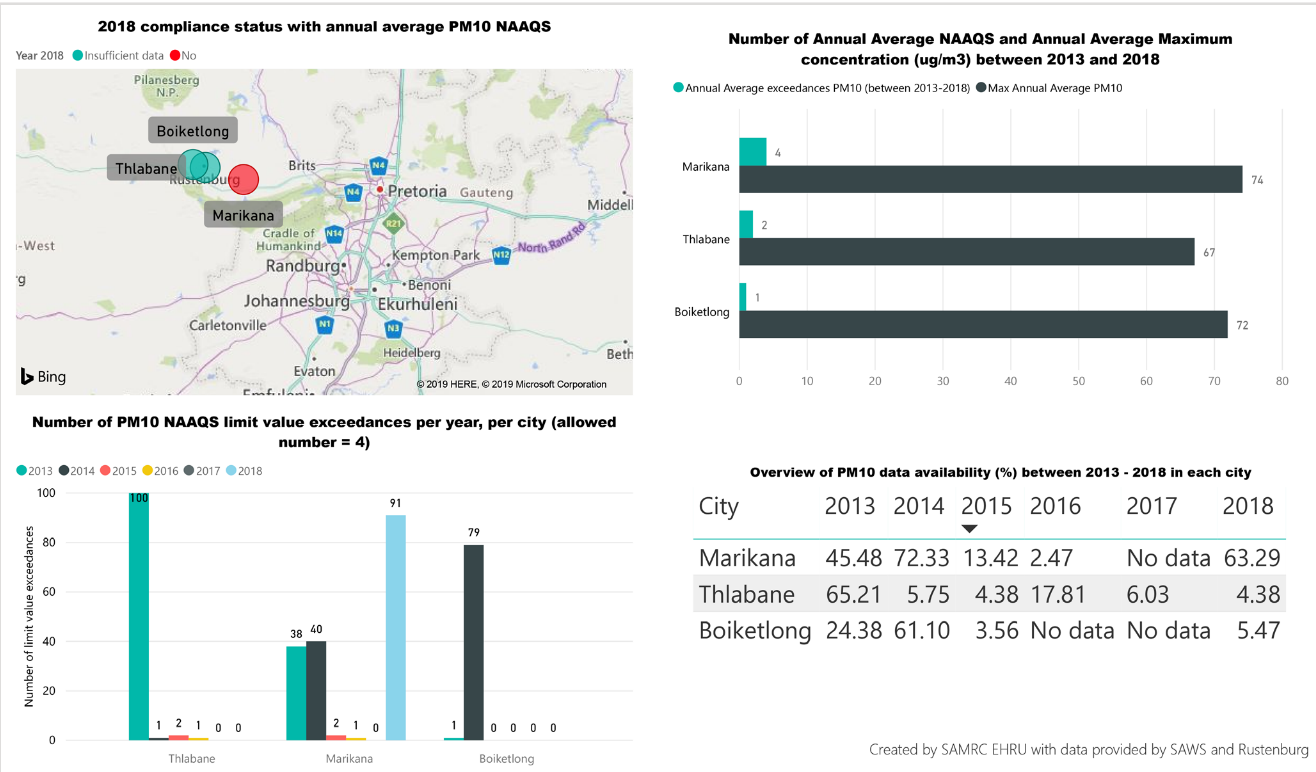

Figure 1: *PM_{10} Rustenburg Local Municipality dashboard: top left – 2018 compliance status by station; top right – annual number of exceedances and annual average maximum PM_{10} concentrations; bottom left – Daily limit value exceedances per year by station; and bottom right – overview of data availability.*

period January – August 2019 reported 125 and 51 daily limit exceedances in Marikana and Boiketlong, respectively (C&M Consulting 2019), supporting evidence that the air quality measured in these towns exceeds legislated limits. More research and higher quality data are needed to confirm whether these data suggest a worsening in air quality in the area. Indeed, data quality and reliability needs attention given that these stations fall within the Waterberg-Bojanala Priority Area where air quality management is deemed a priority of national importance. The 2019 ambient monitoring reports indicate that steps have been taken in Marikana and Boiketlong to increase data availability, reporting 84% and 97% data coverage for the month of August 2019 in both communities (C&M Consulting). Reasons for low data availability are not clear, however, gaps in data could be due to a range of reasons such as power failures, lack of maintenance or calibration leading to, for instance, instrument drift. Even theft / vandalization of instruments is possible. Some monitors are taken out of operation for periods of time to ensure they are fixed when broken, leaving gaps in the data if the monitors are not replaced.

Though the results of this study do add to the available evidence that air quality is poor in these areas, these findings should be interpreted in the context of low data availability. Low data availability can introduce bias into the analysis, if, for example, the available data are representative of a specific season or time of year.

Moving from a simple table (as provided in Table 1) to the visualised dashboard (shown in Figure 1) highlights some of the benefits of using an interactive and easy to understand platform such as Power BI©. The data become visual in 'telling a story'. The dashboard can be created by authorities such as local municipalities or industry to zoom into air quality in a specific space. In some respects, this functionality is similar to that provided by the South African Air Quality Information System but through the use of Power BI© one can change all aspects of data presentation to zoom into more local contexts with more specific analytics.

Power BI© has been used by Worcestershire County Council in the United Kingdom to create an Air Quality Dashboard online (WCC, 2019). Their dashboard goes beyond air quality data and includes number of hospital admissions too. Similarly, the Lancashire City Council considers emissions, asthma prevalence, chronic obstructive pulmonary disease prevalence, and maps for respiratory conditions and emissions on their dashboard for air quality management in Lancashire (LCC, 2019). The Power BI© dashboard could be used by local authorities to analyse and display their data in a similar interactive way to assess air quality in an area. This type of visual can be powerful and may also prompt action to prevent adverse impacts on human health.

Conclusion

The application of Power BI© to PM_{10} data from the Rustenburg Local Municipality helped transform the data into insights and has the potential to consequently trigger actionable efforts with relative ease. Preparation of graphs and tables was simple and these could be inserted into annual progress reports for review and decision-making.

Despite the relatively poor quantity and quality of the available data, some useful information could be extracted about PM_{10} concentrations at the three sites in Rustenburg. Evidence available suggests that more needs to be done to monitor PM_{10} concentrations in the area and ensure compliance with NAAQS.

While we did not conduct any complex or novel analyses for this technical report, we believe we have shown that Power BI© can add value to a "policy / compliance / management" context for quick, easy visualisation of data. Power BI© is user-friendly, easy to understand and to interpret and takes the shape of a dashboard which is currently a tool used globally to help in decision-making.

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